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RESULTS OF THE APOLLO I CENTRIFUGE PROGRAM
(ENGINEERING DEVELOPMENT AND PILOT FAMILIARIZATION)

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston, Texas

March 9, 1964

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(ENGINEERING DEVELOPMENT AND PILOT FAMILIARIZATION)

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SUMMARY

The Phase I Apollo Centrifuge Program was conducted at an unusually early phase in the hardware development cycle in order to obtain a preliminary evaluation of the crew station, suit, and pilot interfaces. Unavailability of properly fitted pressure suits and unavailability of some cockpit displays and controls decreased the fidelity of the simulation.

In spite of the previously mentioned limitations, it was apparent that pressure suit mobility, visibility, and couch compatibility will be major problems in the Apollo program. This situation is more critical for Apollo than for Mercury or Gemini because of the larger Apollo instrument panel and the two-position support couches.

The simulation results indicated that the required manual control operations during launch abort and reentry accelerations are possible; however, improvements in display techniques and control locations are suggested.

INTRODUCTION

The Apollo Centrifuge Program, Phase I, was conducted from October 28 to December 4, 1963, at the Naval Air Development Center at Johnsville, Pennsylvania. Six astronauts accomplished 160 dynamic runs (98 entry profiles and 62 launch aborts). The centrifuge crew station was configured to simulate the spacecraft Commander's position in the Command Module.

The objectives of this program were:

1. To conduct an engineering evaluation of:
    a. The Apollo couch, pressure suit, and harness interfaces.
    b. Acceleration profile acceptability.
    c. Control-display design adequacy.
    d. Preliminary assessment of pilot performance in the manual override mode of operation.
2. To collect baseline medical data of the astronauts' physiological responses during the acceleration profiles.

3. To provide pilot familiarization for selected launch, launch abort, and lunar reentry acceleration profiles and associated control tasks.

Pre-centrifuge familiarization was performed on the fixture and the Evaluator I Complex at NAA, S & ID, Downey, California, before the fixture was shipped to Johnsville. Refresher familiarization was accomplished at Johnsville by running a series of static runs prior to dynamic operations.

Several types of pressure suits were used: the first prototype Apollo phase B suit, the second prototype Apollo phase B suit, the International Latex Corporation (ILC) "state-of-the-art" suit, and the Gemini pressure suit. This variety of suits was utilized because of restricted suit availability, suit fit difficulty, and suit design problems. Additionally, some runs were made in "shirtsleeves".

The program was conducted in two separate phases, launch-abort and entry, because of the limited amount of equipment available at Johnsville. All launch abort profiles were open loop. All lunar entries were open loop prior to a programed G & N malfunction. After the programed failure the entries were closed loop with respect to controls and displays only. Centrifuge operation was open loop for all runs. Eight entry profiles and four launch-abort profiles were programed.

APPARATUS AND EQUIPMENT

Centrifuge Facility

A description of the centrifuge facility and its operation is given in reference 1.

Couch and Restraint Harness

The couch interface to suit and harness was spacecraft configuration. Figure 1 is a photograph of the centrifuge installation. All runs were made with the couch hip and knee angles at 108° and since this proved to be acceptable, no further changes were made.

The couch back was flat rather than contoured. The seat back and armrests were padded for comfort. The couch bank angle was 2° and the resultant "g" vector to the couch back was 8.4° (the gondola inner gimbal was rotated 6.4°).

The couch headrest was the universal, round type to accommodate a variety of helmets. It could be padded with inserts and had a permanent, non-removable pad of about one-half inch. In addition to being padded, the headrest could be adjusted up or down to accommodate different pilots.

The armrests on the couch also had the capability of being adjusted up and down to accommodate various pilots. The translation-abort controller was mounted on the left armrest, and the 3-axis attitude controller was mounted on the right armrest. These could be adjusted fore and aft to accommodate the forearm lengths of the individual pilots. Also, the footrests could be adjusted vertically and the calf support pan could be shimmed to rest against the calves as was required.

The restraint harness used was of the five-point-release design. (See fig. 2.) The chest buckle, which weighed approximately 1.4 pounds and had an area of 20 square inches, constituted the five point release by joining the two shoulder straps, the two chest straps, and the crotch strap together. In addition to these, there was a hip and lap belt combination which fastened in the middle by means of an aircraft type buckle. The legs were restrained by a leg strap about 6 to 8 inches above the knees, and the feet were restrained by means of metal foot-pans. During the program, various forearm and elbow restraints were devised and tested.

Pressure Suits

The primary pressure suit used in this program was the second prototype Apollo phase B suit which was the latest design at the time of the program. (See figs. 3 and 4.) A noticeable feature on this suit is the emergency oxygen supply box located on the back of the helmet. One of these suits, size medium regular, was available for the centrifuge program.

Another suit used was the first prototype Apollo phase B suit, size medium regular. This was similar to the second phase B suit except for the helmet.

A Gemini pressure suit was used for one day in order to make some comparison runs. A fourth suit, the International Latex "state-of-the-art" suit (fig. 5), was worn by the astronauts who could not fit into the Apollo phase B suit. Since the "state-of-the-art" suit was the forerunner of the Apollo suit, it had some similarity, especially in the arms, shoulders, and gloves. The major difference was in the helmet.

Hand Controllers

Minneapolis-Honeywell hand controllers were used in the program. (See fig. 1.) The left hand (translation-abort) controller was fixed in all axes except for the abort (rotational) movement. The right hand (attitude) controller incorporated all switches inside the handgrip. This controller was canted to fit the natural hand position of the command pilot, the neutral position being 10° forward, 7° off vertical to the left and rotated 7° to the left. When the attitude controller was deflected out of detent ± 3.25° in the roll direction during automatic entries, the pilot overrode the automatic system. Full throw of the controller (± 13°) provided the direct mode of operation, while a deflection of 3.25° to 13° resulted in rate command. Therefore, the pilot could override the auto-pilot with either rate command or direct depending on how much roll he commanded. Full rate command roll was 17°/second.

Commanders' Panel Controls and Displays

Except where noted, the location of displays and controls was accurate to within 1 inch of spacecraft location as shown in NAA Drawing V16-976186 dated September 1963; a comparison between this drawing and the main instrument panel is shown in figures 6a and 6b. Figure 6b also shows the main instrument panel divided into subpanels. A brief description of these subpanels follows:

Subpanel 1: The altimeter was active for the launch-abort phase only and seems to have been satisfactory in its present location.

Subpanel 2: This panel constituted the Entry Monitor System (EMS) display that was active for entries. The .05 g light and the red and green corridor lights, which were on this display, functioned. The ΔV Slew switch was inoperative. The EMS was designed to allow the pilot to monitor the automatic entry and to take over manual control if the Guidance and Navigation System allowed the "g-velocity" (g-V) trace to become tangent to the high g or exit rays which were permanently drawn on the integral faceplate. (See fig. 7.) Two sizes of EMS faceplates were evaluated in the program; $6\frac{1}{2}$" × $4\frac{1}{2}$" and $3\frac{1}{2}$" × 5". In addition, the faceplates were evaluated as to color, and type and thickness of the exit and high "g" rays.

The EMS "g-V" trace showed the profile as it was actually flown by the pilot. The first transit of the trace across the faceplate covered the velocity range from 36,000 ft/sec to 24,000 ft/sec, at which time the trace reset in 11 seconds to the left side. The second transit of the trace covered the velocity range from approximately 23,000 ft/sec to 11,000 ft/sec.

Subpanel 3: The emergency detection system (EDS) panel active components were the master caution light, the abort light, and the Saturn I fuel pressure indicator.

Subpanel 4: The flight director attitude indicator (FDAI) was designed by Minneapolis-Honeywell. This indicator was of Apollo design and had six needles, one each for pitch, roll, and yaw rates and one each for pitch, roll, and yaw errors. For launch-aborts, full scale indication for all rate needles was ± 5°/sec and for all error needles, full scale was ± 5°. Full scale indication on the pitch and yaw rate needles for entry was ± 5°/sec while the roll error and rate needles on entry displayed ± 25° and ± 25°/sec, respectively. All needles were mechanized although the 8-ball itself was not activated due to the lack of slip rings and computing equipment.

Subpanel 5: The event stack was operational for the launch-abort phase only. This panel was not spacecraft hardware. The components were larger than the ones actually planned for the spacecraft, and therefore, the event stack had to be extended to the bottom of the Commander's panel. This resulted in shifting some of the event stack telelights down several inches and shifting some switches and telelights on Subpanel 9 to the left several inches. These differences are shown in figures 6a and 6b.

Subpanel 6: None of the components on this panel were active.

Subpanel 7: The "thrust normal" switch and the "thrust on" telelight on this panel were active; other components were not.

Subpanel 8: This was the blank area forward of the translation-abort control housing.

Subpanel 9: Stabilization and control system (SCS) control mode select panel. The channel "backup rate" and "disable" switches were active as were the monitor, SCS ΔV, G & N entry, and SCS entry telelight controls. All other components were inactive. This panel had been shortened somewhat to provide space for the event stack. Among the components shifted to the left on Subpanel 9 was the SCS entry telelight switch.

Subpanel 10: Only two lights were active on the caution matrix panel and these were the coupling display unit (CDU) and the inertial measurement unit (IMU) lights. Due to the limited size of the centrifuge commander's panel as a whole, the caution matrix was moved to the left approximately three inches.

Subpanel 12: This panel was not active.

Subpanel 14: This panel contained the guidance and navigation computer display and keyboard. Due to its late arrival it was active only during the last two days of the program. This panel was used with several entry profiles. Only a limited number of parameters were displayed and these consisted of "g", time, roll angle, velocity, altitude, and range-to-go. In addition, a computer caution light and a warning light were displayed. The readouts were not in code but in direct numbers. All the numbers were $\frac{3}{4}$ inch in height, and were green displayed against a gray background. These parameters were updated and displayed every 2 seconds during the course of the entry.

Subpanel 16: Active components on the crew safety panel were the oxidizer dump, auto abort enable, fuel dump activate, reaction control system (RCS) purge, and RCS control, switches. With the exception of the oxidizer dump and auto abort enable, these were 3-position switches spring-loaded to the center position.

PROCEDURES

Launch-Abort Phase

The following is a brief description of the launch-abort profiles as run in this program. The primary indicator for rates and attitude errors during the launches was the FDAI.

All aborts were manually initiated by the pilot in response to the abort indication. Reference 2 contains a more detailed presentation of these profiles. A summary of launch-abort runs is shown in table I.

1. Normal Launch (including Service Module abort). Ten of these profiles were run. The procedure consisted of a normal launch up to 200 seconds; this included first stage burnout, staging, second stage ignition, and tower jettison. The Service Module abort was the only abort performed after the launch escape tower was jettisoned. Recordings for this profile are shown in figure 8.

2. Pad Abort. Twelve dynamic pad aborts were performed. The sequence was initiated at T-6 seconds, and continued through escape motor burn, drogue parachute deploy, main parachute deploy, and fuel dump. The initial "g" load was + 10g ("eyeballs in") followed by a rapid drop to -1g ("eyeballs out"). The profile was complete in about 20 seconds. Recordings are shown in figure 9.

3. Max Q Abort. Twenty dynamic Max Q aborts were performed. Indications for these aborts were instrument unit (IU) power failure or yaw rate feedback loss occurring in the range of 60-80 seconds after lift-off. The launch vehicle (L/V) excessive rate light was illuminated when rates exceeded 5°/sec on the FDAI. This profile included launch escape motor burn, drogue parachute deploy, main parachute deploy, and the sequence was complete at fuel dump. This profile, at escape motor burnout, changed from + 6g "eyeballs in" to - 3.2g "eyeballs out" in about 5 seconds. Recordings are shown in figure 10.

4. High Altitude Abort. Twenty dynamic high altitude aborts were performed. The programed failure for these aborts was either a hardover engine or a yaw guidance failure. Again, the L/V excessive rate light illuminated when rates exceeded 5°/sec on the FDAI. Peak "eyeballs in" g on this profile was + 10 followed by - 0.5g "eyeballs out" seconds later. The acceleration profile was concluded after escape motor fire and tower jettison. Recordings for this profile are shown in figure 11.

Entry Phase

The entries were open loop for both the centrifuge and displays prior to a programed G & N malfunction. After the programed failure, the pilot task was to take manual control by means of the 3-axis controller and fly the remainder of the entry manually. The controls and displays after take-over were closed loop while the centrifuge remained open loop. As soon as possible after take-over the pilot switched from the automatic (G & N) entry mode to the manual (SCS) entry mode.

In addition to the programed G & N failures, stability and control system (SCS) failures were introduced into many of the entry profiles. These failures included "open" or "continuous" signals on the rate gyros and required the pilot to correct the condition by activating the body mounted attitude gyros (BMAG) in the respective channel. Other SCS failures included "open" or "continuous" signals on switching amplifiers. These required the pilot to disable the affected channel and manually control with the direct mode of operation. Indications of these failures came mostly from the FDAI rate needles, but some roll channel failures could also be detected by means of the lift vector indicator.

The range of entry accelerations varied from + 5g to + 15g. For all entry profiles except the Service Module abort, the pilot task after manual take-over was to control to a constant 5g plateau by reference to the "g-V" trace. The entry runs are summarized in table II.

Following is a brief description of the entry profiles:

1. CE100 (Exit Ray Violation). Sixteen dynamic runs of this profile were accomplished. The profile consisted of a normal G & N entry through the first peak of + 10g with the programed failure occurring at + 6.7g following the initial peak. At the failure point, the "g-V" trace, as displayed by the EMS (fig. 7), became tangent to an exit ray. Recordings are shown in figure 12.

2. CE101 (Service Module Abort). Eleven dynamic runs were made. This profile represented one type of service module abort and reached a + 15g peak. The pilot task was to keep the lift vector indicator full up (0°) throughout the profile. The manual control take-over point for this profile was indicated by a deviation from the maximum-lift roll attitude. Recordings for this profile are shown in figure 13.

3. CE102 (Bank Angle Command Failure). Eight dynamic runs were made. This profile represented a G & N bank angle command failure at + 6g on initial entry into the atmosphere. The lift vector indicator, due to the G & N failure, rolled off the full up lift (0°) position at the + 6g level and the pilot was asked to immediately take manual control and correct the lift vector. Otherwise, the spacecraft could have continued to roll to an adverse lift vector and develop excessive acceleration. The centrifuge was programed on the assumption that the pilot allowed the lift vector to move approximately 30° off full positive lift; therefore, the centrifuge peak "g" was + 12. However, if the pilot initiated control before this time, lower acceleration values appeared on the EMS trace. On the other hand, if he allowed the error to exceed 30°, higher acceleration values appeared on the "g-V" trace. Recordings for this profile are shown in figure 14.

4. CE104 (Normal G & N Entry). Fourteen dynamic runs were made. This profile represented a normal, 1,000 nautical mile G & N automatic entry. No failures were programed; however, provisions were made which permitted the pilot to manually fly this entry with the attitude controller. The G & N roll command information was displayed on the FDAI roll attitude error needle (see fig. 6a). Recordings are shown in figure 15.

5. CE106 (High g Ray Violation). Fourteen dynamic runs were made. This profile was a normal G & N entry through the first + 10g peak after which the spacecraft "skipped out" of the atmosphere in a normal subcircular ranging maneuver; it reentered some 200 seconds later. At the + 4.5g level after reentering the atmosphere a G & N malfunction caused the trace to become tangent to a high g ray. Recordings for this profile are shown in figure 16.

6. CE 107 (Exit Ray Violation). Fourteen dynamic runs were made. This profile represented another exit ray violation, the failure occurring at + 6.8g coming off the + 8g initial peak. Recordings are shown in figure 17.

7. CE110 (Bank Angle Command Failure). Twelve dynamic runs were accomplished. This profile again represented a bank angle command failure on initial penetration. The failure occurred at + 6g. The pilot task was to manually control the lift vector indicator to zero until peak g was reached and to fly to + 5g thereafter. The centrifuge acceleration for this profile peaked at + 14g followed by a constant + 5g level until termination of the run. Overall, this run probably represents the most severe acceleration environment covered in the program. Recordings for this profile are shown in figure 18.

8. CE114 (Flight Path Angle Too Small). Nine dynamic runs were made. This profile demonstrated an entry in which the flight path angle was too small. Unless corrective action was taken, the spacecraft would never have remained in the atmosphere, but would have "skipped out" at supercircular speed. Corrective action in this case was to roll the lift vector to full negative lift (180°) to allow penetration and then control to a constant + 5g level thereafter. The failure indication, a red corridor light on the EMS, occurred at + 0.2g on initial entry. A typical run is shown in figure 19.

RESULTS

Couch and Restraint Harness

In general, the couch proper, not including the armrests and headrest, offered adequate support; comfort did not noticeably degrade with time for centrifuge occupancy up to four hours, which was the limit used in this program. No "submarining" down into the couch occurred on any of the profiles. Although the couch support was adequate for this program, it is doubtful that a flat back would provide support for "eyeballs-to-the-side" acceleration. Some pilots developed red spots on their back because of minimum contour support on "eyeballs in" g's.

In the course of the program, it was found that the longer-trunked men sat several inches too high with respect to the instrument panel. (This can be seen in a comparison of figs. 3 and 5.) The medium regular phase B suits were too small for these pilots and, therefore, the ILC "state-of-the-art" suit had to be utilized. (See fig. 5.) Even though the helmet vision restriction with this suit was not nearly as pronounced as it was with the phase B suit, it required one or more inches of headpad insert to see the instrument panel when the suit was unpressurized. The vision lines for the ILC suit are shown in figure 20.

The "heart-to-head" (aortic-retinal) angle could be greatly varied by use of headpad inserts on the headrest. This angle proved to be very critical; in some cases it approached 15° and resulted in a severe restriction to g tolerance and vision. The ILC helmet with a one-inch headpad insert resulted in approximately the same "head-to-heart" angle as was obtained utilizing the second prototype Apollo phase B helmet with no headpad insert. This angle was marginal at high g's.

The couch headrest should be custom fitted to the helmet and should be designed to offer lateral support for the head. The pilot should be able to rotate his helmet in the headrest. The headrest design should provide recesses for any protrusions from the back of the helmet. When these criteria are met, the Commander's entire panel should be visible with no headpad inserts.

Two and one-half inches more forward adjustment will be required on the right and left-hand controllers. In order to allow the pilot to adjust the right-hand controller forearm support length, a friction lock or other simple means should be provided.

The tests showed that the calf support plate on the lower couch was not needed for most men. Removal of the calf support and some redesign could perhaps satisfy requirements for all pilots and eliminate some weight.

The restraint harness provided effective restraint for all runs; however, it was unsatisfactory for several reasons. The most serious shortcoming for this harness was that it could not be hooked up by the crew member without assistance. He could not see or reach the chest buckle.

On boost-aborts, the pilot came off the back of the couch approximately 2 to 3 inches when going to "eyeballs out" g, and the helmet, which weighed about 10 pounds, came forward noticeably; however, no discomfort was noted at the -3.2 g ("eyeballs out") level reached in this program. If subsequent data indicate the possibility of an excessive "eyeballs out" g, then a head restraint should be considered.

Additional problems with the restraint harness are listed below:

1. There are pressure points at both hips where the hip belt rests against the side hip plates.

2. Elbow restraints would be desirable and should be considered.

3. The inverted metal "V" at the hips, where the hip and lap belt tie together, caused pressure points on both sides.

4. The added weight of the chest buckle was tiring and made respiration difficult. It should be eliminated. A strap arrangement in this area would be desirable.

5. All straps to the chest buckle became loose during runs and had to be tightened frequently.

6. The pilot could not reach the leg straps when the chest harness was tight.

7. It was difficult to tighten the chest straps due to reach restrictions.

8. Chest buckle interference prevented helmet tie-down cable adjustment when the restraint harness was tight. This interference also tended to "cock" the helmet to one side when the suit was pressurized.

9. It was difficult to release the hooks on the leg straps because the hooks had to be rotated into the leg in order to be released. These hooks were also too heavy.

10. The restraint harness straps need to be longer to afford a "grip" when tightening.

11. The couch should have adjustable forearm restraints to offer side support for the arms and to aid in controlling the spacecraft.

Pressure Suits

The second prototype Apollo phase B suit proved to be totally unsatisfactory. It was impossible for some pilots to get their arms into the armrests. This was primarily because of the shoulder design in the suit. A major suit modification is required to integrate the arms with the armrests. When the phase B suit was pressurized, the neutral position of the forearms was 6 inches to the side and 10 inches forward. When the arms were forced back into the armrests, the wrist rings caused pressure points, wires across the back of the arms caused pressure points, and pressure points existed inside the elbows. The pilot unknowingly held full left roll, pitch up was not attainable, and the stick could not be gripped for yaw control due to suit restrictions.

The emergency oxygen supply box attached to the back of the second phase B helmet did not fit the headrest. Helmet structure restricted vision markedly, and a $1\frac{3}{4}$-inch headpad insert was required to enable the pilot to see the Commander's lower instrument panel. The resulting head angle (estimated at 15°) caused some pilots to gray out at about 9g. Even with the $1\frac{3}{4}$-inch headpad insert the SCS control panel could not be seen when the suit was pressurized. These vision lines are shown in figure 21. On further testing, it was found necessary to remove all headpad inserts to get an acceptable "aortic-retinal" angle. Consequently, the lower 8 to 10 inches of the Commander's panel was not visible even unpressurized.

Further problems with the second Apollo phase B suit, many of which are shown in figures 2 to 4, are listed below:

1. The vent tubes down the back caused pressure points.

2. The helmet tie-down cable interfered with the restrain harness assembly.

3. The leg straps fouled fittings on the suit leg.

4. The glove palm band should be better integrated with the stick in order to improve control feel.

5. The 90° elbow at the inlet-outlet hose plate forced the plate into the ribs and interfered with the armrest.

6. Fittings and plugs on the back of the helmet fouled the headrest.

7. Wrist action was limited when pitch up control was attempted.

8. The neck ring caused pressure points against the shoulders.

9. An excessive temperature gradient existed in the suit. The back ventilation was excessive while the hands, feet, and right front side were insufficiently cooled.

10. The pilot could neither see nor reach the restraint harness chest buckle.

11. The helmet airflow was directed into the eyes.

12. The helmet microphone picked up noise from the airflow.

13. Cross reach was restricted to the suit centerline.

14. The restraint harness could not be fastened by the pilot without assistance.

The first prototype Apollo phase B suit had no emergency oxygen box attached to the back of the helmet and therefore, integrated somewhat better with the headrest. However, panel visiblity was much more restricted. With the $1\frac{3}{4}$-inch headpad insert, the lower 6 to 8 inches of the Commander's panel could not be seen, unpressurized. (See fig. 20.) Other problems with this suit were essentially the same as with the second prototype suit.

The Gemini pressure suit allowed the pilot to see the entire Commander's panel without headpad inserts; the arms could also be placed into the armrests by the pilot when the suit was pressurized. With this suit, the pilot could reach everything on the panel that could be reached with the Apollo suit. (This suit would not fit the longer-trunked pilots, however.)

Hand Controllers

The translation-abort handle was satisfactory for initiating abort. However, as previously mentioned, more forward adjustment will be required for the larger pilots. The breakout force for abort could have been slightly higher, but the detent position, amount of travel, and other aspects were satisfactory. (The translation action of this controller will have to be evaluated on other programs where the task is applicable.)

The most prevalent comment regarding the 3-axis controller was that it needed a definite change in force gradient between rate command and direct (soft stops). Soft stops would have been invaluable for detecting the full rate command stick position. Also, the grip was improperly shaped and was too large for the gloved hand. The cutout in the handgrip for the glove palm piece was too shallow. For improved gripping, the surface should be knurled.

Pitch up action of the 3-axis controller was very difficult; this could have been due in part to the pressure suit and in part to the pivot point being in the center of the palm. There was no decrement in handling this controller at different g levels. This controller also needed more forward adjustment for the larger pilots and, as previously mentioned, there should be a simple mechanism to allow the pilot to adjust the forearm support length for pressurized as well as unpressurized operation.

The amount of travel ($\pm 13°$) of the 3-axis controller was excessive in all axes for direct control. This made manual damping difficult because full stick throw was required. The stick breakout forces, gradients, and pivot point should be evaluated for orbit operations, docking, and other tasks before any firm conclusions are made.

Commander's Panel Controls and Displays

As was found in the static simulations, the EMS display was not operationally acceptable. While the trace was being drawn, it was very difficult to detect tangency and therefore, there were many doubts as to when to take over manually. (See fig 7.) CE100 and CE106 were especially difficult in this regard. This resulted in the takeover of many trajectories in which the "G & N" was still functioning normally. Also around the tangency point, the EMS trace required a considerable amount of uninterrupted attention causing other displays to be neglected.

Otherwise, it can be stated that with the best head angle (ILC "state-of-the-art" helmet, or standard aircraft flight helmet, with no headpad inserts), the EMS trace and lift vector arrow were visible at all g levels. The small faceplates sufficed just as well as the large ones, and there was no problem picking up the trace after scanning other indicators. Dark EMS faceplates were preferable to the light colored type. The exit and high g rays should be long broken lines of medium thickness. The "g-V" trace should be twice as thick as these rays. The ΔV Slew switch on the EMS was beyond the reach of some pilots.

It was found that the abort light needed to be much brighter and located closer to the center of the scan pattern. The master caution light should also be brighter. It also was located too far to the left and could not be seen at high g.

The FDAI provided sufficient scale resolution and the "fly to" needle presentation on this instrument was adequate. While the scale presentation of the other needles was good, a non-linear scale on the roll attitude command-error needle may be desirable for entry, and should be considered for future investigations. More contrast is needed between the roll error needle and the 8-ball. The present color scheme makes it difficult to see during the critical entry phases. The pitch error needle "zero" position and the pitch rate needle "zero" position should be located at the center of the FDAI face with the "up" and "down" scales linear. Scalemarks are needed on all the error needles, especially at the center and full scale points. It would be desirable for the pitch and yaw error needles to display "downrange" and "crossrange" errors during the entry phase of the mission.

Since the FDAI was the main instrument for detecting control system failures, it should be mentioned that it was impossible to differentiate between some gyro and electronics failures by using the indications from this instrument. This forced the pilot to isolate these failures by means of "trial and error" switching procedures which required much time and effort even at 1g. More time and effort were required, of course, as acceleration increased.

It was found that the telelights as displayed on the event stack needed to be more consistent. Some of these lights before being pushed, some lights after being pushed, and some did not light at all. This was quite confusing and, when used in conjunction with the switches on the crew safety panel (16), had no logical sequence. These displays did not lend themselves to the rapid responses required after abort. The panel should be designed to eliminate the present random sequencing between the event stack and the crew safety panel. The nomenclature on all lights should be readable even when the lights are not illuminated. Generally, all the lights on the event stack were too dim.

All switching on the SCS control mode select panel (9) that must be accomplished under "g" load must be performed with the left hand. The right hand must be kept on the 3-axis controller in order to override the G & N system should a failure occur. The SCS entry switch, even offset as it was to the left, was very difficult to reach because of the required cross reach. In fact, none of the switches on the SCS control mode select panel (9) were in a good, accessible spot although these could be reached at a considerable sacrifice of attention and control. Due to the interference of the translation control box, the "channel disable" and "backup rate" switches were difficult to activate even in the unpressurized suit. Although later design has relocated these switches (roll "backup rate" over roll "channel disable", pitch "backup rate" over pitch "channel disable", et cetera) and respaced them, some reach problems may still exist.

It is considered mandatory that the SCS entry switch be activated immediately after a G & N failure since, even if the pilot blacked out, the spacecraft would be limited in roll by the rate deadband. If the G & N were left engaged, as is currently necessary above 7 and 8 g's, high roll rates would be possible.

Another serious problem with subpanel 9 is that of panel visibility. At 1g, in the ILC "state-of-the-art" suit, as much as $1\frac{3}{4}$ inches of head padding was required in some cases to see this panel (fig. 20).

The spacecraft design should provide for a "manual G & N entry" control mode of operation. This would allow the pilot to manually fly the entry if the autopilot had malfunctioned independently of the G & N system (SCS entry cannot be used in this case because the G & N roll command signal is not presented on the FDAI in the SCS mode). The "manual G & N entry" switch should be as accessible as the SCS entry switch.

The caution matrix lights were readily visible, however, the lettering on all these lights was too small; on many, the lettering was confusing. A simple one or two words to describe the failure would be much better.

The MIT G & N computer display and keyboard was readable up to 10g and the pilots could read the panel without rotating their head. The pilot could reach and push the keys at 8g. The pilot could, if required, fly by reference to this display as it is presently located. It is therefore considered essential to keep this panel reading in direct numbers rather than in code. There is some doubt as to the necessity of displaying range, velocity, or altitude to five figures on entry since they are changing so rapidly. The panel readout numbers could perhaps be $\frac{1}{8}$" smaller and a black rather than a gray background would provide more contrast. The "g" readout should be capable of backing up the .05g light. The caution and warning lights should be color coded.

The design of the crew safety panel (16) is very poor. Too many critical switches are located too close together; the same is true for the nomenclature (fig. 6a). This resulted in hesitancy and difficulty in finding the proper switch when it was needed. After abort, the action of reaching back and forth between the event stack and this panel, and, at the same time, trying to remember which switch goes up and which down, was illogical and confusing. More design effort is needed in this area.

The Commander's panel should include an aircraft type mechanical accelerometer to monitor accelerations.

CONCLUDING REMARKS

The launch-abort tasks covered in this program presented no appreciable difficulty to the pilots, and the corresponding accelerations were classified as "quite mild" by most of them. No breathing problems, loss of vision, or grayout problems appeared during these runs.

There was no physiological restrictions which affected the pilots' ability to control the entry profiles utilizing the second prototype Apollo phase B suit with no headpad inserts; however, generally speaking, vision was restricted at 10 to 12g to a 12 to 15-inch-diameter circle at the panel. At 15g, in many cases, vision was restricted to an area not much larger than the lift vector indicator. The best "aortic-retinal" angle could be obtained with ILC "state-of-the-art" helmet (or a standard aircraft flight helmet) with no headpad inserts. Under these conditions, the EMS trace and lift vector indicator were clearly visible at all g levels.

The second prototype Apollo phase B suit was totally unsatisfactory because of the shoulder design. Also, the structure of the helmet on this suit severely restricted vision of the Commander's lower panel.

A large scan pattern was required for entry, even if SCS failure did not occur. Since it was necessary to include the SCS control mode select panel in the crosscheck when SCS failures did occur, this doubled the size of an already large scan pattern. The pilot could not see gross motions on the EMS and FDAI simultaneously and, therefore, missed any abnormal movements which might have occurred on one, while concentrating on the other. Since the "g-V" trace required almost constant attention during the critical period following the initial entry peak, the rest of the panel was necessarily neglected.

All the longer-trunked pilots sat too high with respect to the Commander's panel. This may require lowering the entire seat structure. The present high eye level made it impossible, with no headpad inserts, for the pilots to see the SCS control mode select panel (9) even in the

ILC "state-of-the-art" suit. When the head was padded to see this subpanel, the high eye level still created a difficult scan pattern.

The switches on the lower, center section of the Commander's panel were very difficult to reach at 5g. Crossreach in the pressurized suit was restricted to the centerline, however, by using both hands, all controls except the ΔV Slew switch on the EMS were within the reach radius of the pilots. Also, in order to make pressure suit operation easier, all switches on the Commander's panel should be "up" in the normal position. This would allow the pilot to move a switch down quickly for a malfunction without taking time to rotate his wrists. Working the left hand inboard and around the translation controller housing in order to activate the "backup rate" and "disable" switches was difficult. More clearance should be provided.

The scan pattern for launch was also excessive. The master caution and abort lights should be moved closer to the FDAI, the primary instrument for launch. The interaction required, after abort, between the event stack and the crew safety panel, was a totally uncoordinated, unacceptable presentation. Redesign is required in this area.

The blank space in the center of the Commander's panel should be utilized to better group displays and controls and reduce the size of the scan pattern; this would do much toward simplifying the entry and launch tasks.

The great majority of the problems discussed in the foregoing report are quite evident under static conditions. Further centrifuge programs should not be considered until all this hardware is modified to function properly at 1g.

REFERENCES

1. Kuehnel, H. A., and Glover, K. E.: Project Mercury Program Description and Discussion for the Astronaut Acceleration Training Program III (Mercury-Redstone Mission Training). NASA-Project Mercury Working Paper No. 189, May 8, 1961. CONFIDENTIAL

2. Thomas, J. B.: Apollo Centrifuge Program Outline, Phase I (Engineering Development and Pilot Familiarization) NASA General Working Paper No. 10,015, October 4, 1963.

TABLE I.- SUMMARY OF CENTRIFUGE RUNS

BOOST - ABORT

CARPENTER	Normal Launch & S/M Abort	Pad Abort	Max Q Abort	High Alt Abort
ILC suit Unpressurized	S 1 D 1	S 2 D 2	S 2 D 3	S 2 D 3
CONRAD				
Shirtsleeves	S 1 D 1	S 2 D 1	S 2 D 1	S 2 D 1
2nd Phase B Unpressurized	D 1	D 1	S 1 D 3	S 1 D 3
YOUNG				
Gemini Suit Unpressurized	S 1 D 1	S 1 D 1	S 1 D 1	S 3 D 1
Gemini Suit Pressurized	D 1	D 1	D 1	D 1
1st Phase B Unpressurized	D 1	D 1	S 1 D 2	D 2
MCDIVITT				
Shirtsleeves	S 3 D 1	S 1 D 1	S 1 D 1	S 2 D 1
ILC Suit Unpressurized	D 1	D 1	S 1 D 3	S 1 D 3
BORMAN				
Shirtsleeves	S 2 D 1	S 1 D 1	S 2 D 2	S 2 D 2
1st Phase B Unpressurized	D 1	D 2	S 1 D 3	S 1 D 3
Total Static Boost Aborts	8	7	12	14
Total Dynamic Boost Aborts	10	12	10	20

S - Static

D - Dynamic

TOTAL STATIC BOOST-ABORTS - 41

TOTAL DYNAMIC BOOST-ABORTS - 62

TABLE II.- SUMMARY OF CENTRIFUGE RUNS ENTRIES

CARPENTER	CE100	CE101	CE102	CE104	CE106	CE107	CE110	CE114
Shirtsleeves	S 2 D 1	S 1 D 1	S 1 D 1	S 1		D 1	D 1	D 1
2nd Phase B Unpressurized	S 1 D 1	S 3 D 1		S 2 D 1	S 2 D 1		S 1 D 1	
ILC Suit Unpressurized						S 1		
ILC Suit Pressurized	S 1 D 1	D 1	D 1		D 2	S 1 D 1		S 4
CONRAD								
Shirtsleeves	S 1 D 2	S 1		S 1 D 3	D 1	D 1	D 1	
2nd Phase B Unpressurized		S 2	S 2 D 1	S 1 D 1	S 1 D 1	S 4		S 3
2nd Phase B Pressurized		D 1			D 2		D 1	D 2
ILC Suit Pressurized	D 1	D 1	D 1	S 1		S 2 D 1		
YOUNG								
Shirtsleeves		D 1		D 1			D 1	D 1
2nd Phase B Unpressurized	S 2 D 1	S 1 D 2	S 1 D 1	S 1 D 1	S 1 D 2	D 2	S 1 D 1	S 1 D 1
2nd Phase B Pressurized	S 2	D 1	D 1	D 1	D 1	S 1 D 1	D 1	D 2
MCDIVITT								
Shirtsleeves	D 1		D 1	S 1	D 2	D 1		
ILC Suit Unpressurized	S 1 D 2	D 2	S 1 D 1	S 1 D 1	S 2 D 2	D 2	S 1 D 2	D 2
ILC Suit Pressurized	D 1			D 1				
WHITE								
Shirtsleeves	S 4 D 5			S 2 D 4		S 5 D 4	D 3	
Total Static Entries	14	8	5	11	6	14	3	8
Total Dynamic Entries	16	11	8	14	14	14	12	9

S - Static

D - Dynamic

TOTAL STATIC ENTRIES - 69

TOTAL DYNAMIC ENTRIES -98

TABLE III.- NOTATIONS AND SYMBOLS

Symbol	Units	Definition	Nominal Value
M_x	ft-lb	Thrust moment, X_B axis	±960
M_y	ft-lb	Thrust moment, Y_B axis	±866
M_z	ft-lb	Thrust moment, Z_B axis	±878
G	g's	Total sensed load factor	0 to 20
ϕ_E	degree	Attitude error, Roll	25
p_B	degree/sec	Roll rate, body axis	±50.0
q_B	degree/sec	Pitch rate, body axis	±50.0
r_B	degree/sec	Yaw rate, body axis	±50.0
t	second	Time	
V	ft/sec	Velocity	0 to 50,000
α	degree	Angle of attack	±10
β	degree	Angle of sideslip	±10
γ	degree	Flight path angle	±180

Taped Variables

Symbol	Units	Definition	Range
G	"g's"	Total sensed load factor	0 to 20
V	ft/sec	Velocity	0 to 50,000
ϕ_c	degree	Commanded roll attitude	±180
γ	degree	Flight path angle	±10
ω	Rad/sec	Centrifuge arm command	0 to 3.2

TABLE IV.- NOMENCLATURE

AMAL	Aviation Medical Acceleration Lab.
NADC	Naval Air Development Center
G & N	Guidance and Navigation
SCS	Stabilization and Control System
EMS	Entry Monitor System
RCS	Reaction Control System
FDAI	Flight Director Attitude Indicator
E-1	Evaluator 1, the C/M mock-up used for atmospheric flight phase simulation at NAA, S & ID, Downey, California
BMAG	Body Mounted Attitude Gyro
EVENT A	Sanborn Recorder Channel to record gyro failures, BMAG switch actuations, pilot takeover and entry control mode.
EVENT B	Sanborn Recorder Channel to record amplifier failures and channels disabled.

FIGURE 1: CENTRIFUGE COUCH AND RESTRAINT SYSTEM

FIGURE 2: RESTRAINT HARNESS CHEST BUCKLE

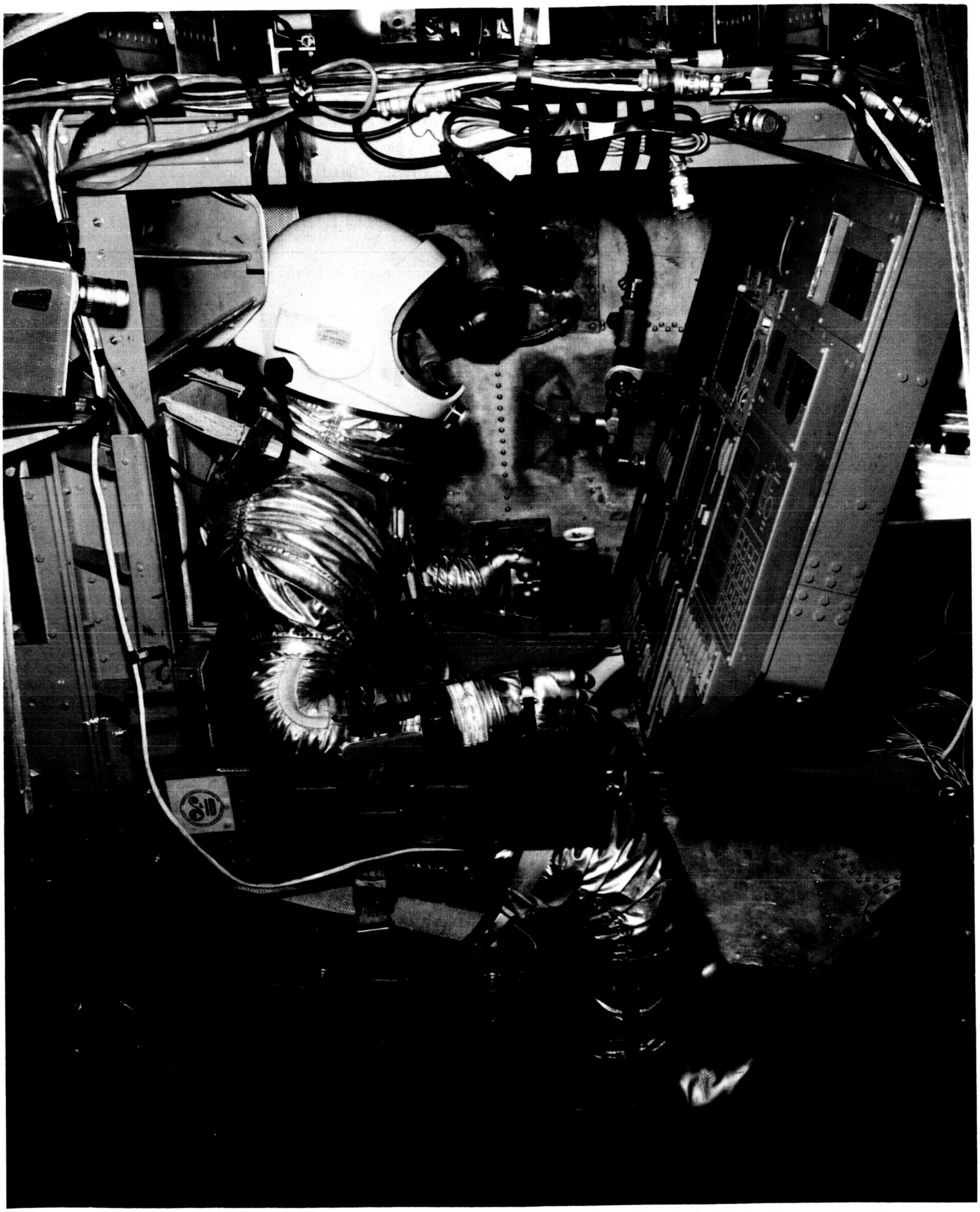


FIGURE 3: SECOND PROTOTYPE APOLLO PHASE B SUIT-UNPRESSURIZED

FIGURE 4: SECOND PROTOTYPE APOLLO PHASE B SUIT-PRESSURIZED

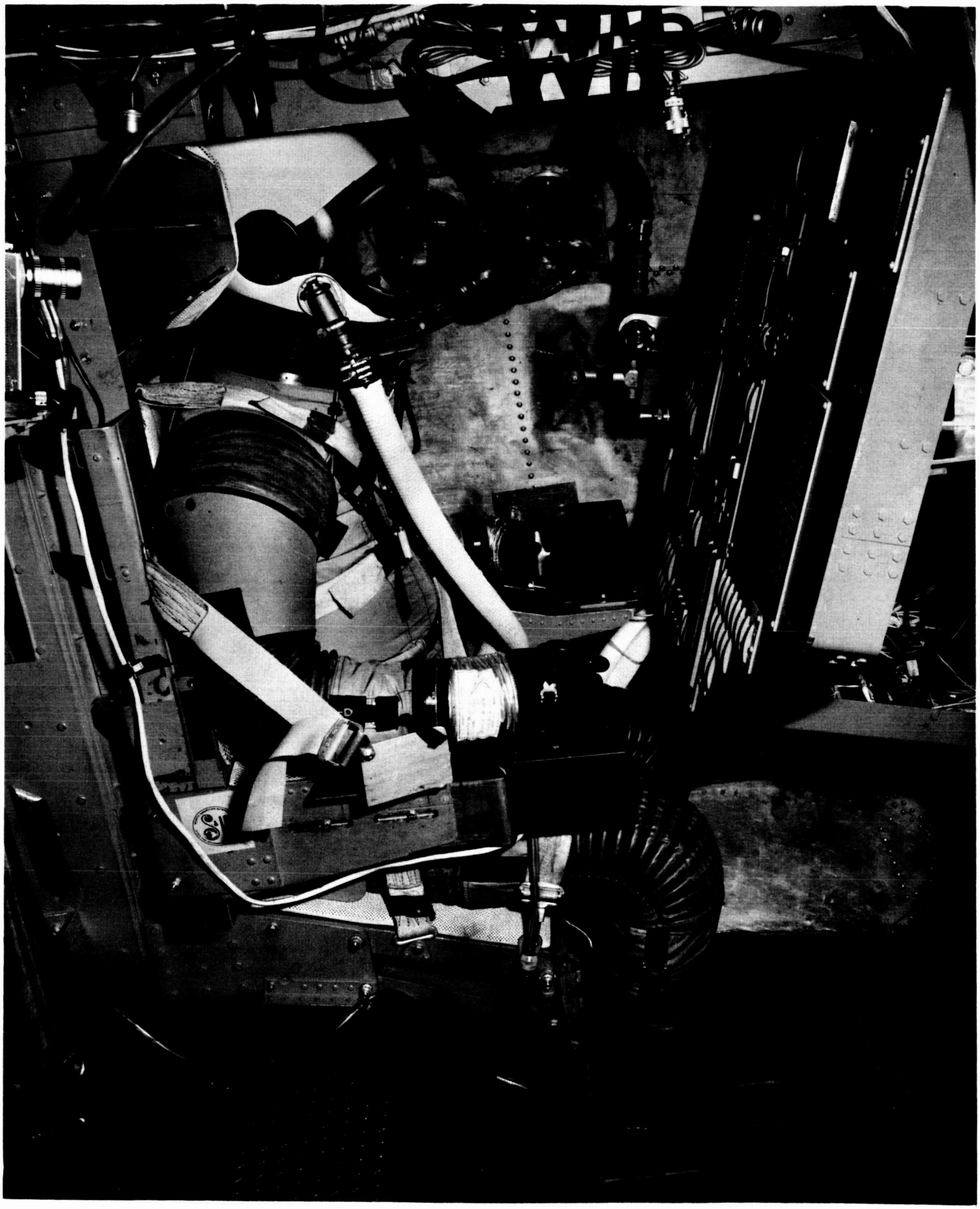


FIGURE 5: INTERNATIONAL LATEX CORP. "STATE-OF-THE-ART" SUIT – UNPRESSURIZED

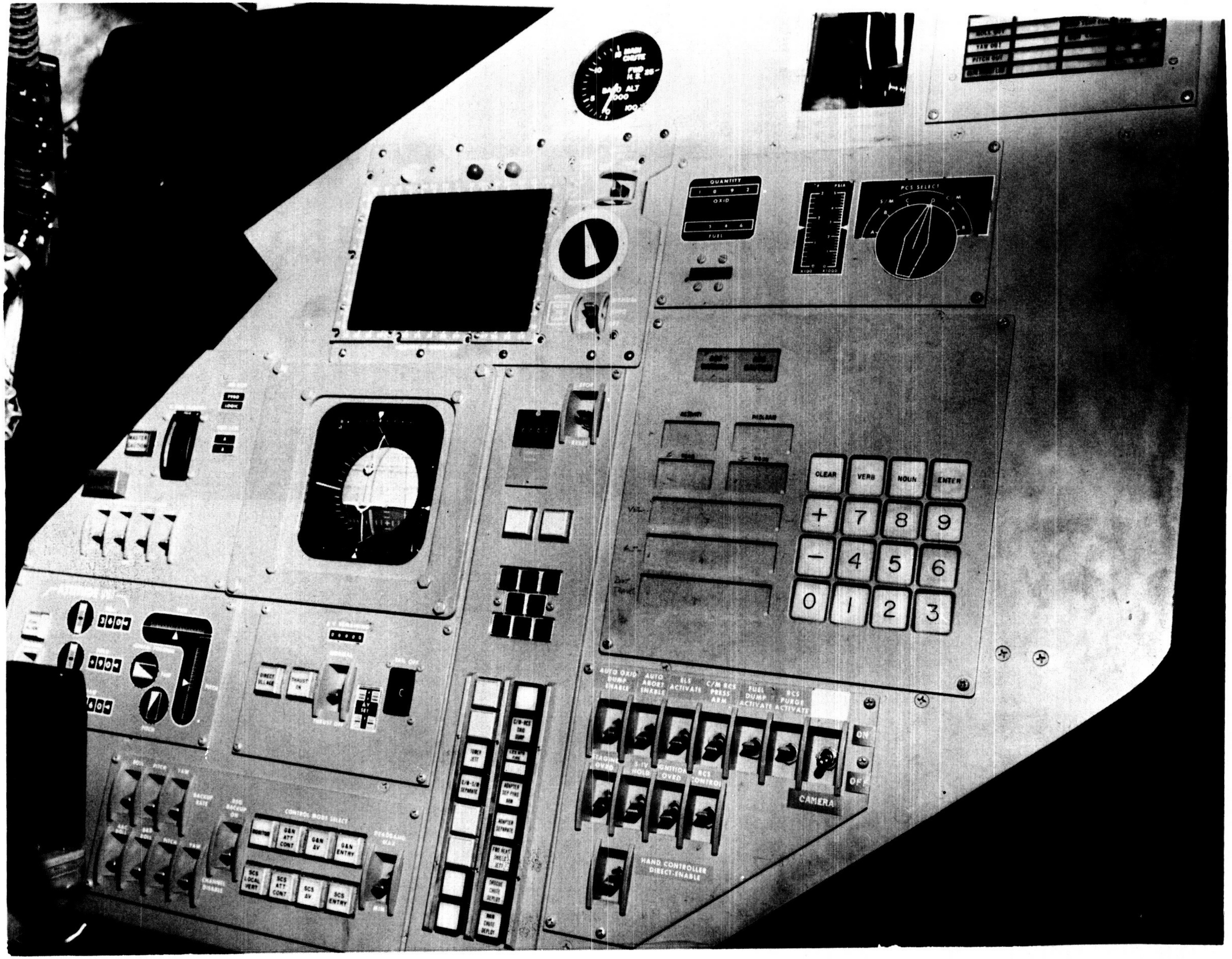


FIGURE 6a: PHOTOGRAPH OF CENTRIFUGE COMMANDER'S PANEL

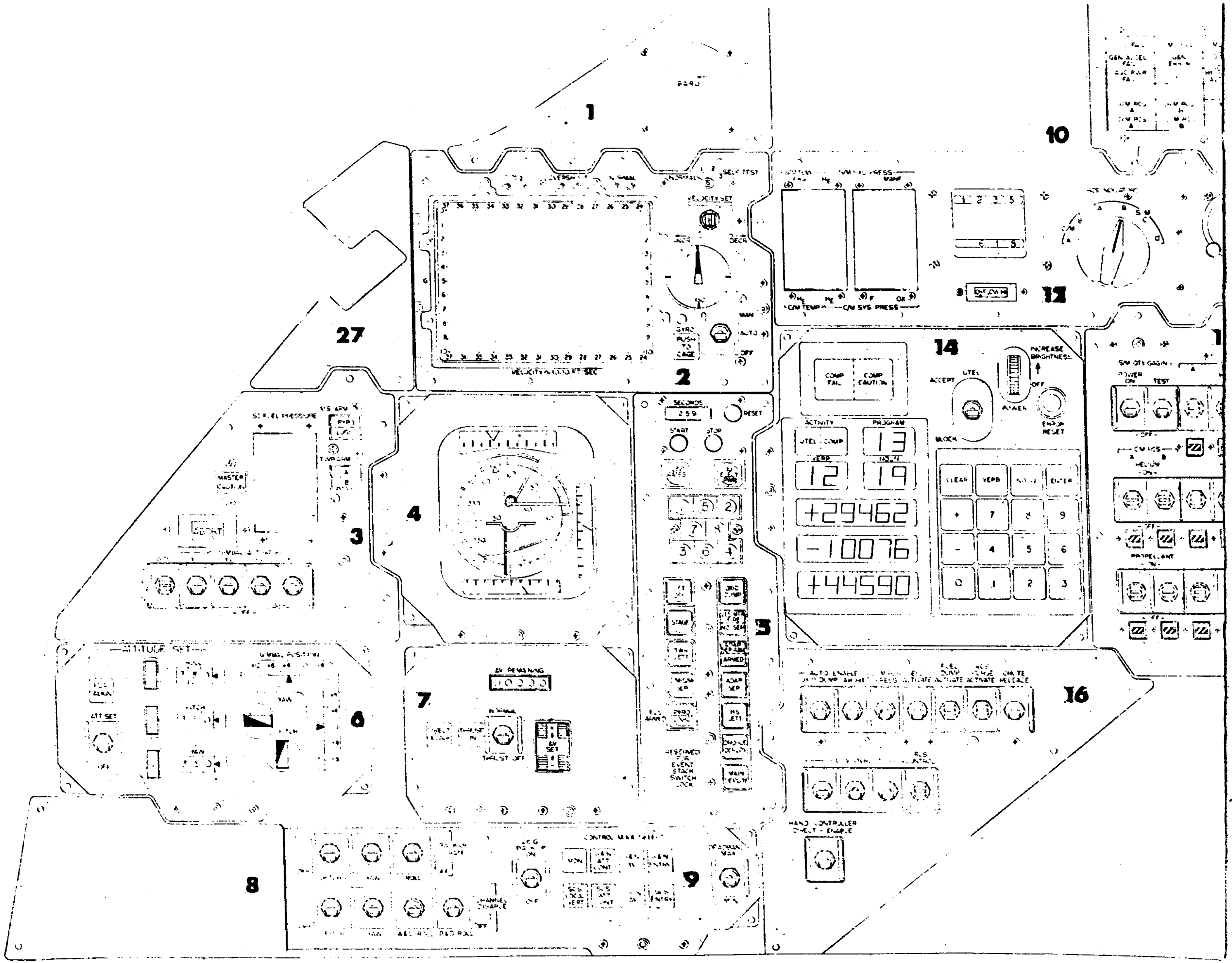


FIGURE 6b: COMMANDER'S PANEL PER NAA DWG. V16-976186, SEPT. '63

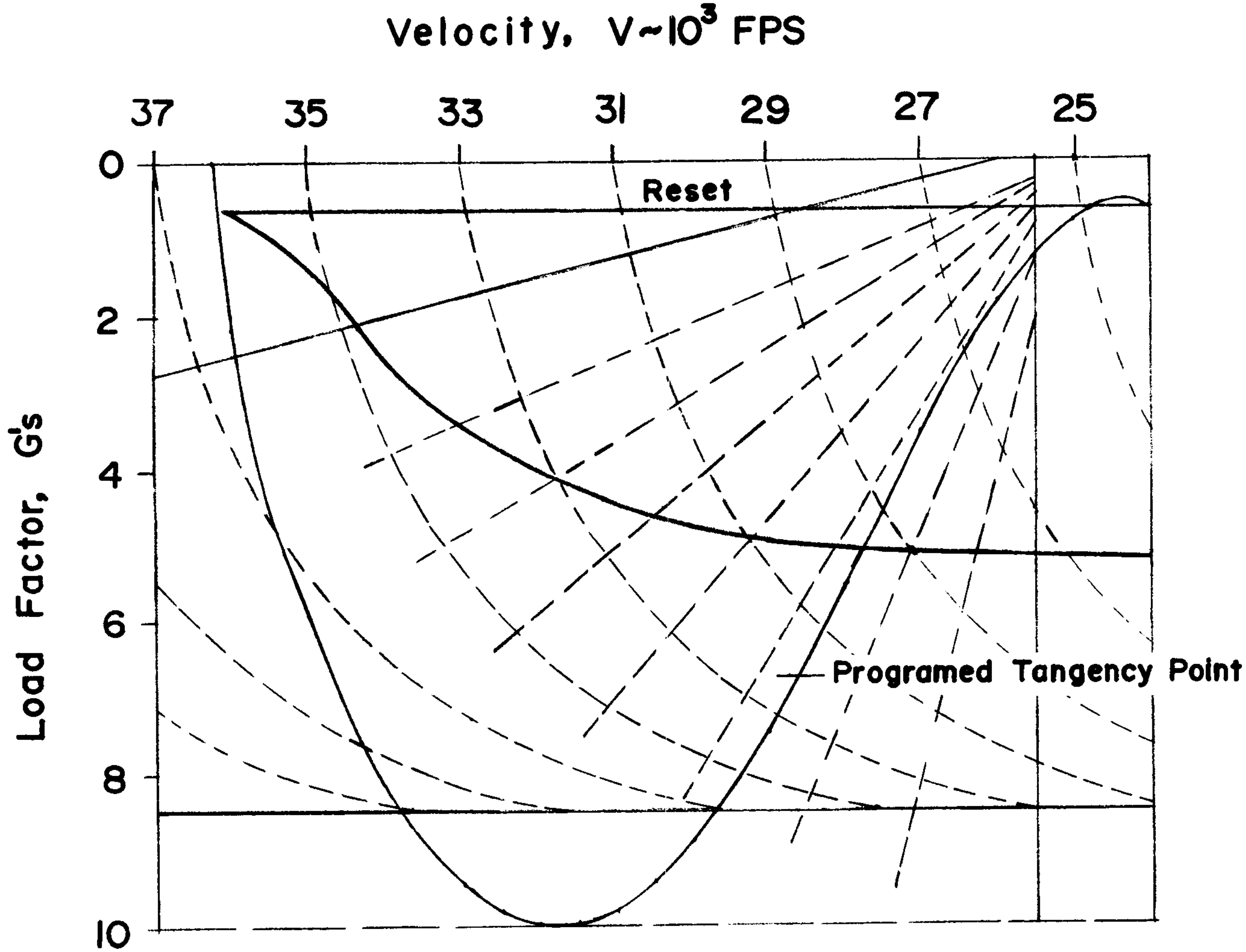


FIGURE 7, CE 100:
DRAWING OF ENTRY MONITORING SYSTEM FACEPLATE

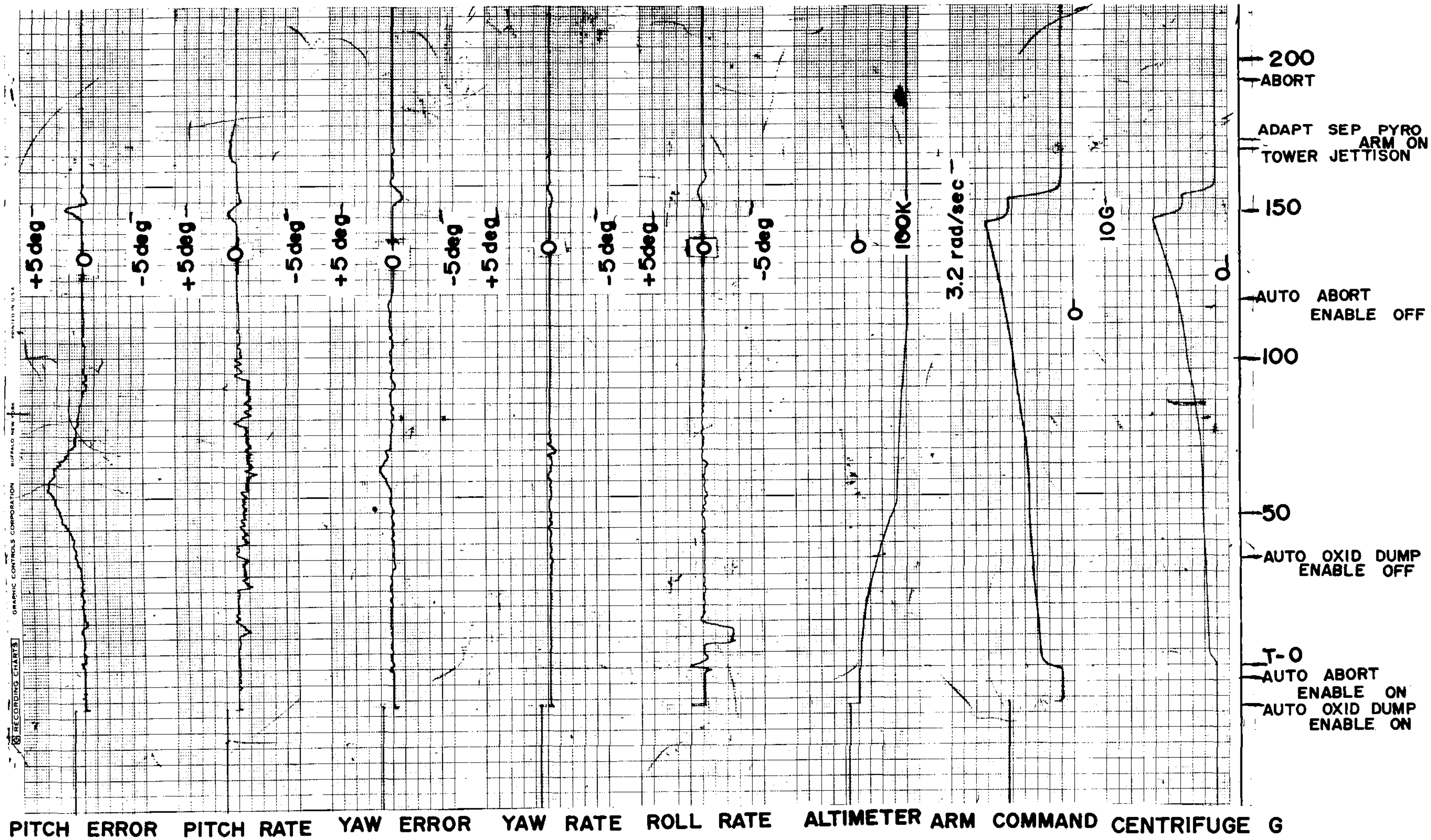


FIGURE 8

DATA RECORDED FOR NORMAL LAUNCH AND SERVICE MODULE ABORT

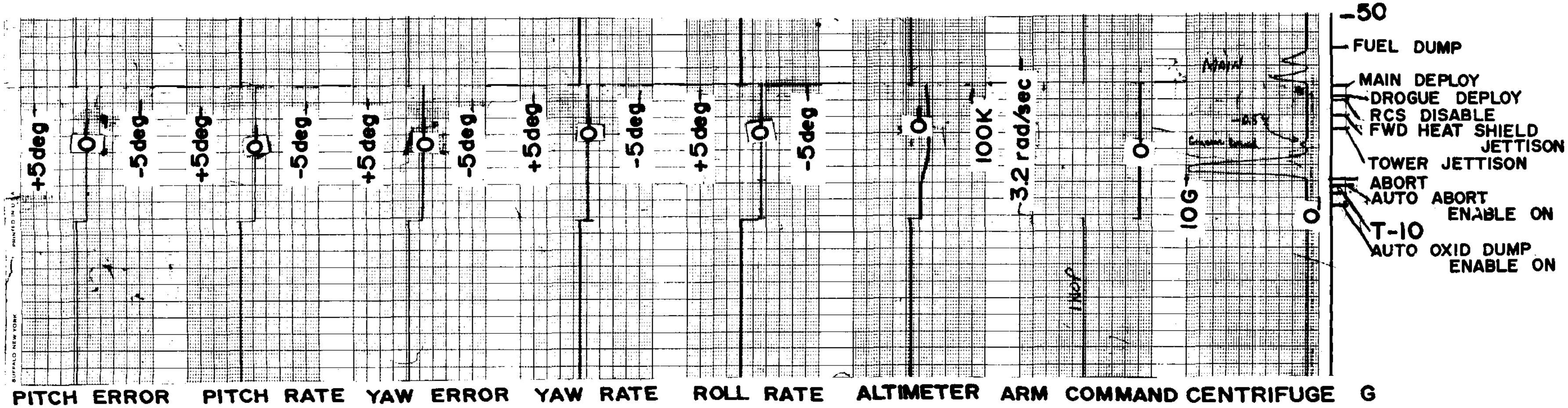


FIGURE 9
DATA RECORDED FOR PAD ABORT

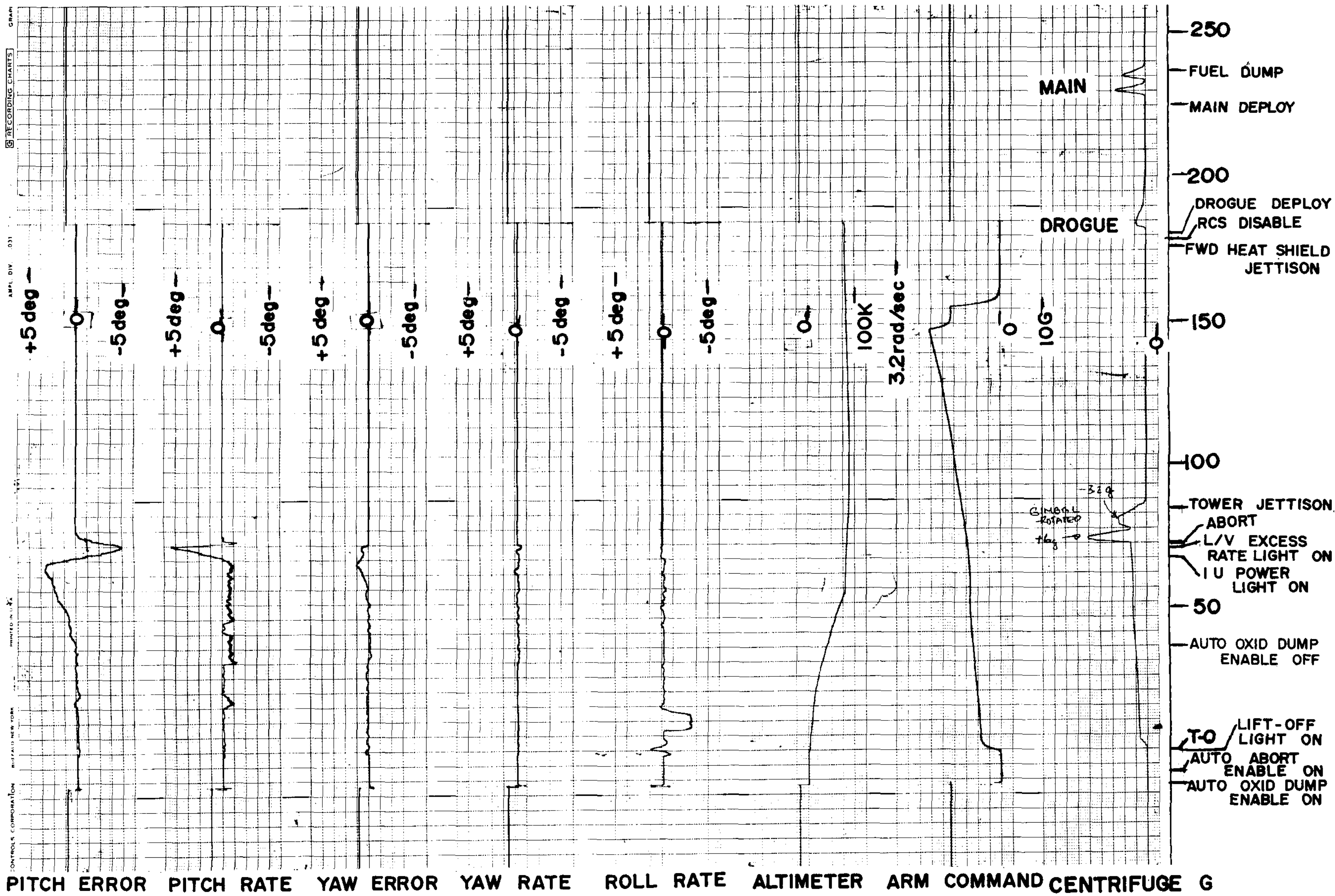


FIGURE 10 DATA RECORDED FOR MAX Q ABORT

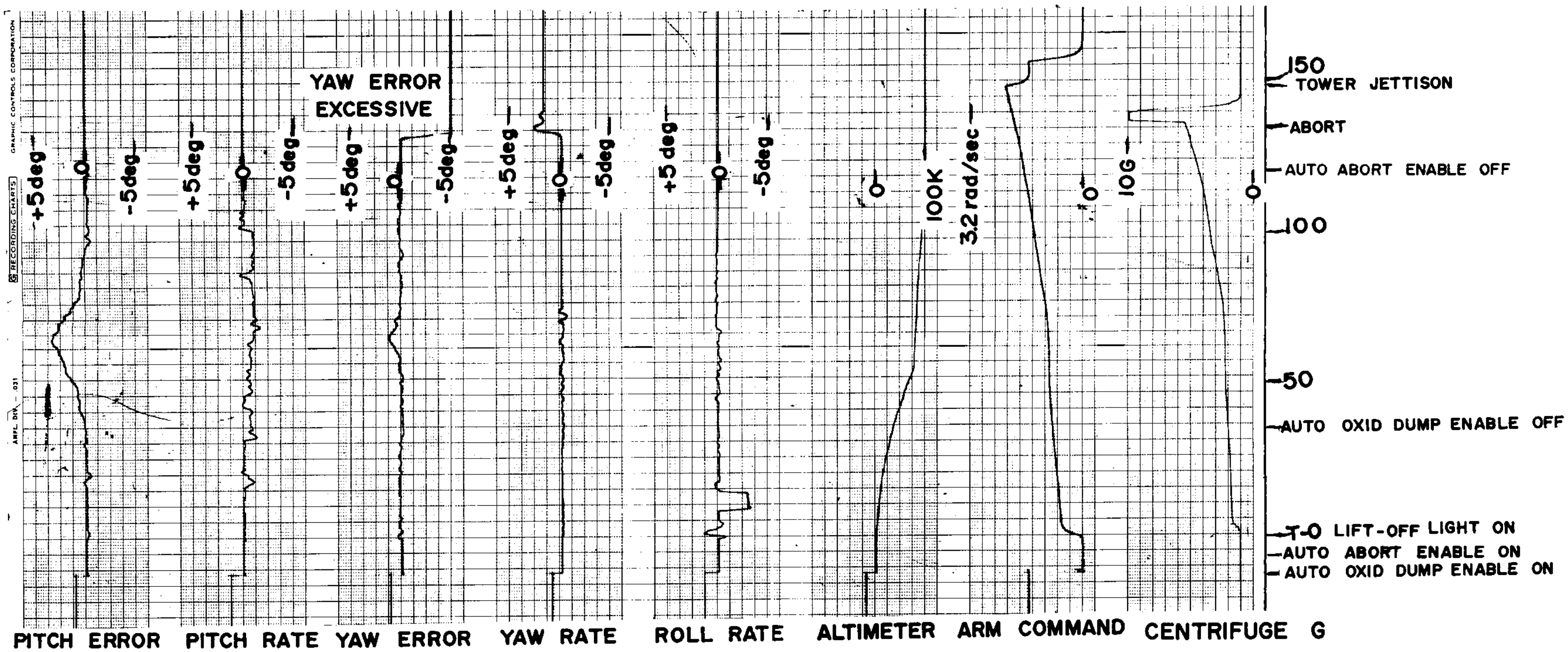
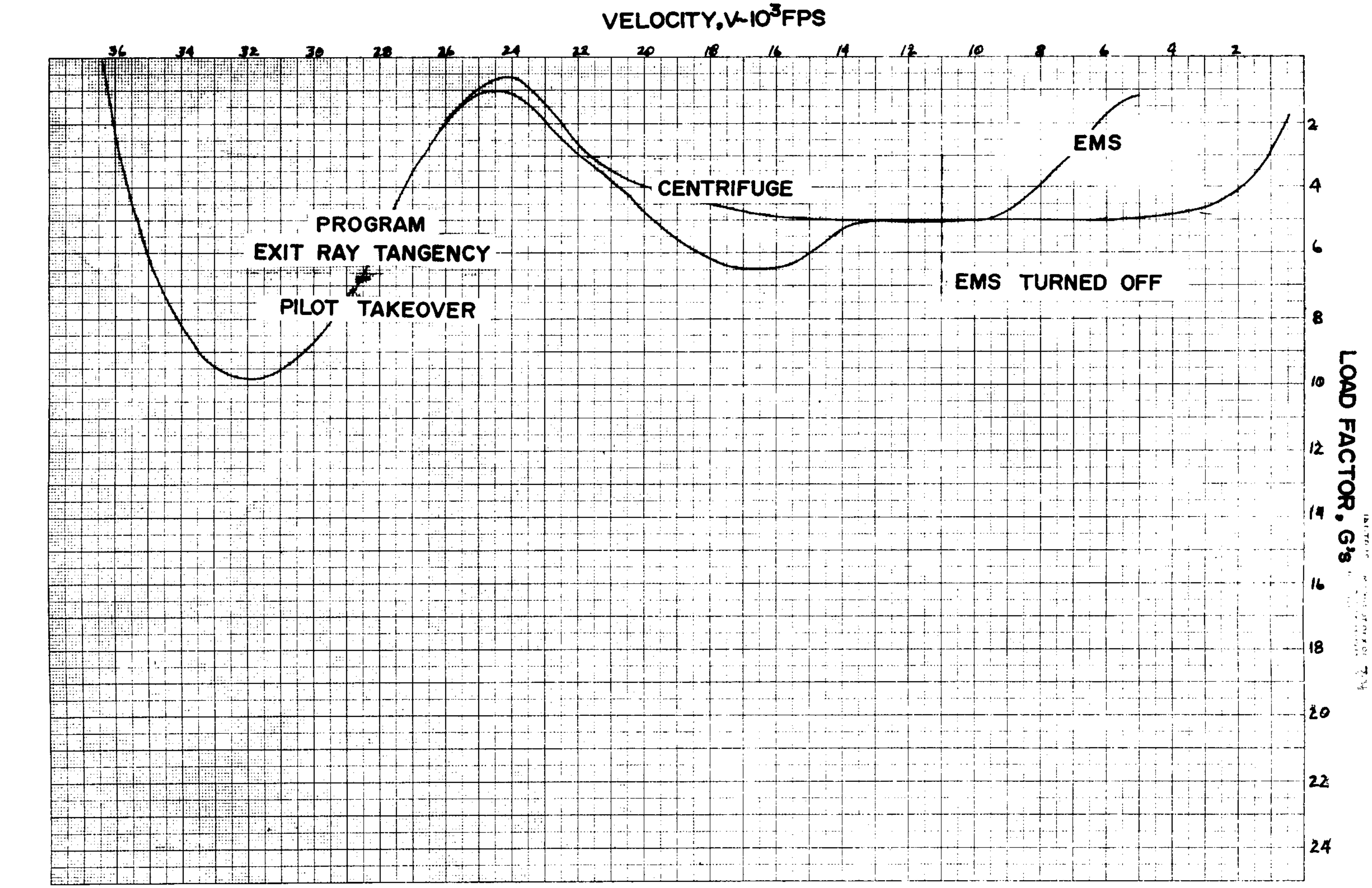
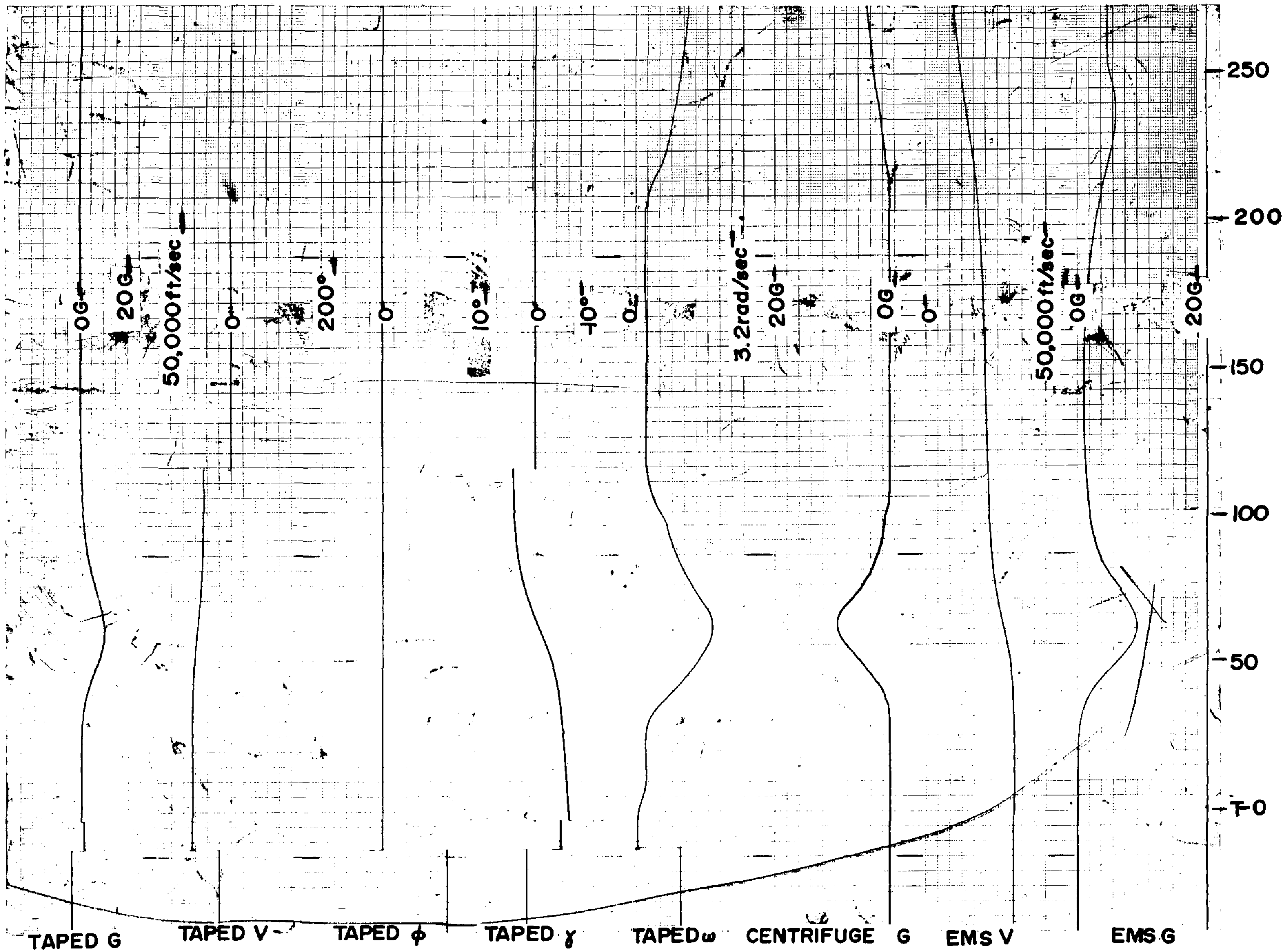


FIGURE II
DATA RECORDED FOR HIGH ALTITUDE ABORT

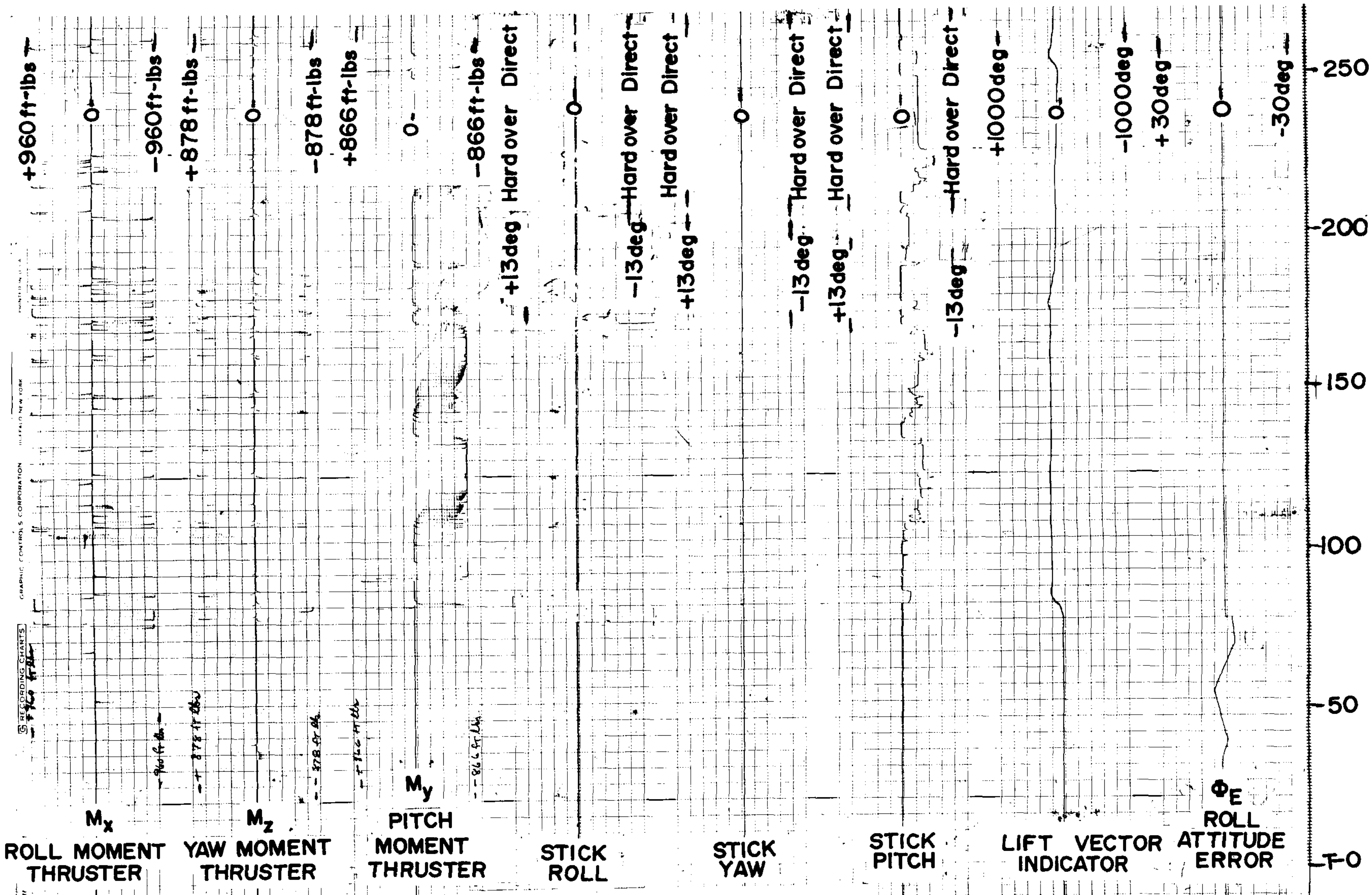


(a) RECORDER NO. 1

FIGURE 12 - CE 100 ~EXIT RAY VIOLATION (10g PEAK)

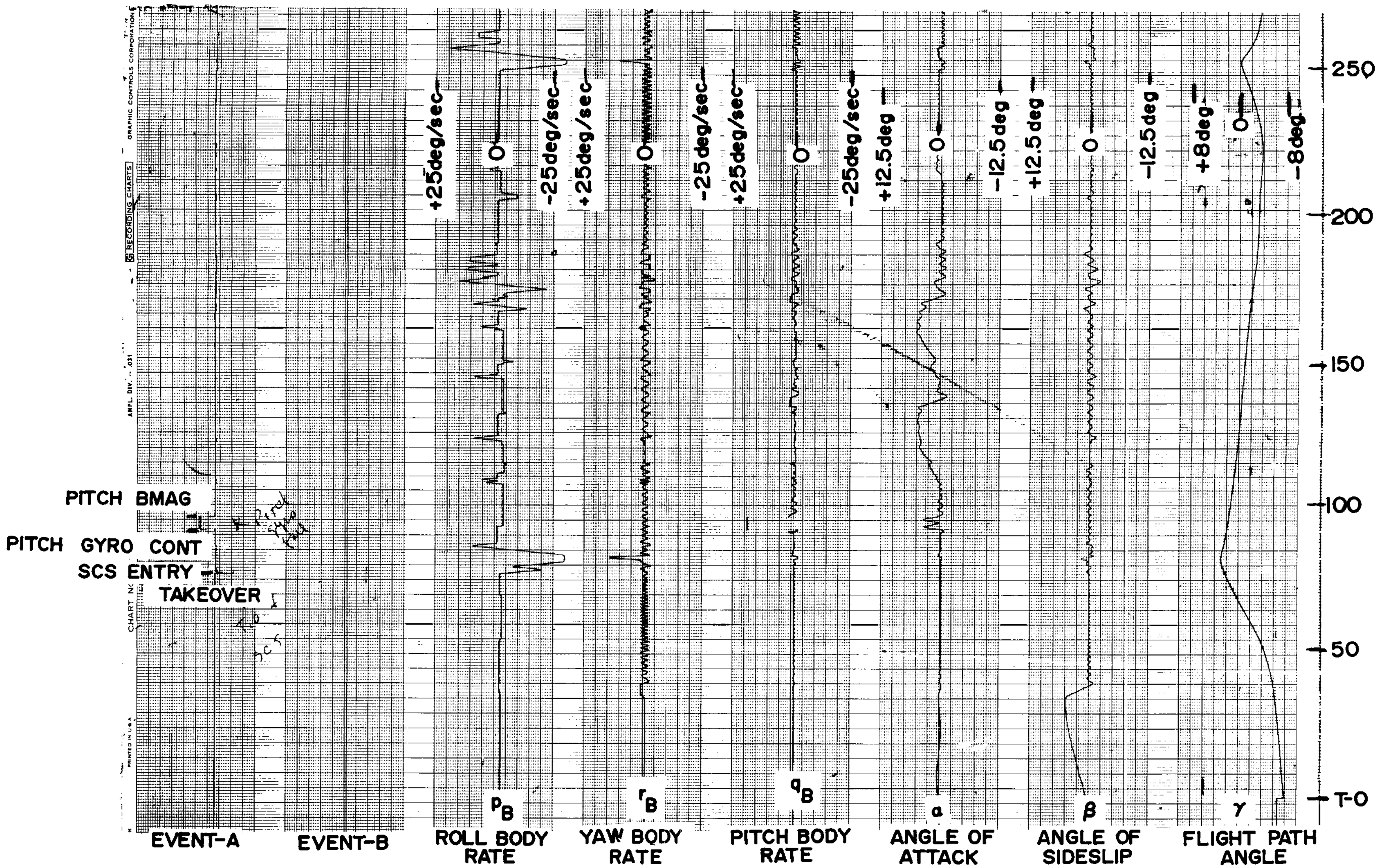


(b) RECORDER NO. 2
FIGURE 12- CONTINUED

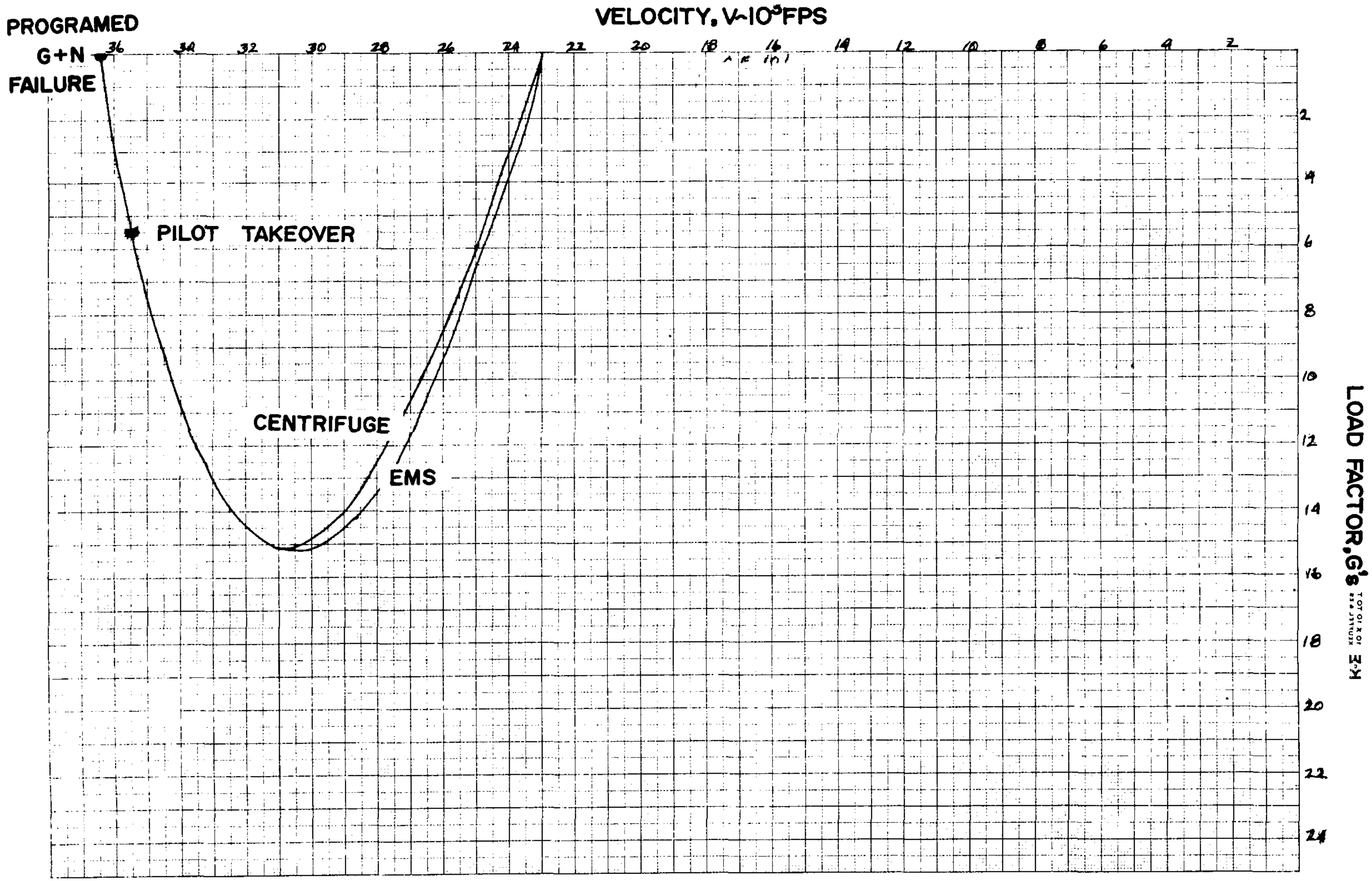


(c) RECORDER NO. 3

FIGURE 12 - CONTINUED

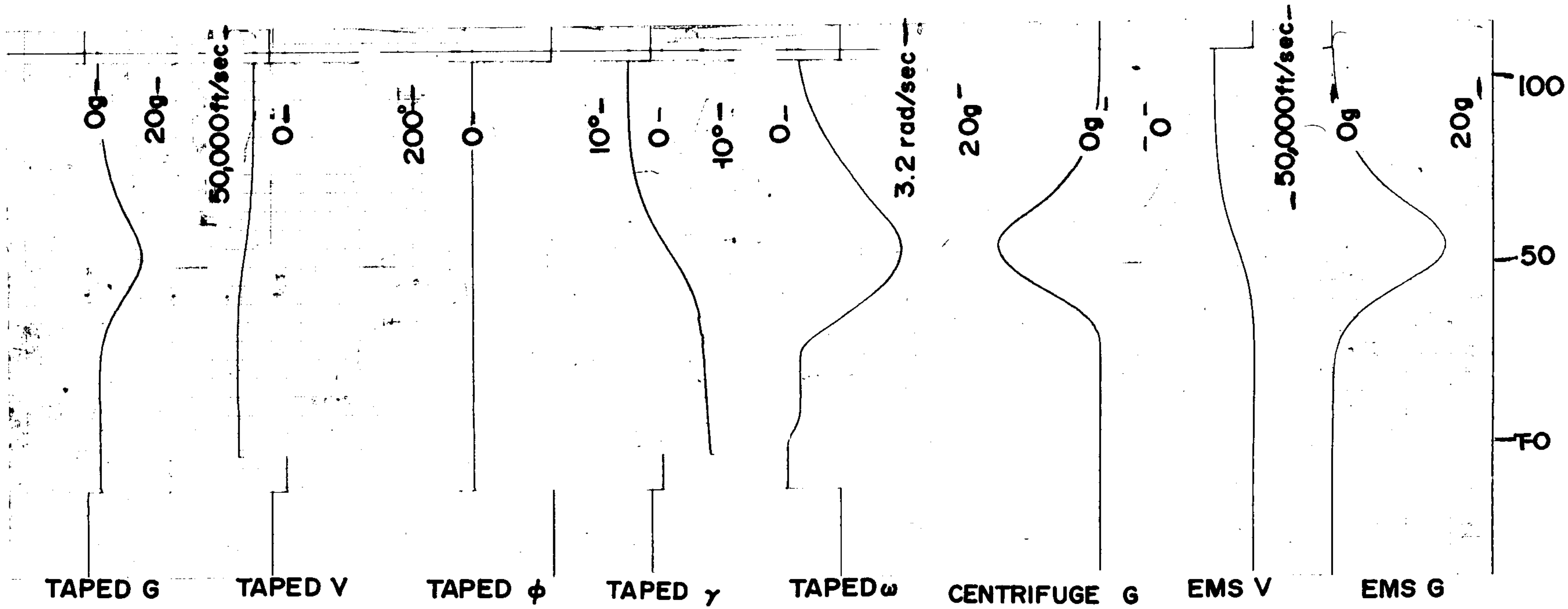


(d) RECORDER NO. 4
FIGURE 12-CONCLUDED

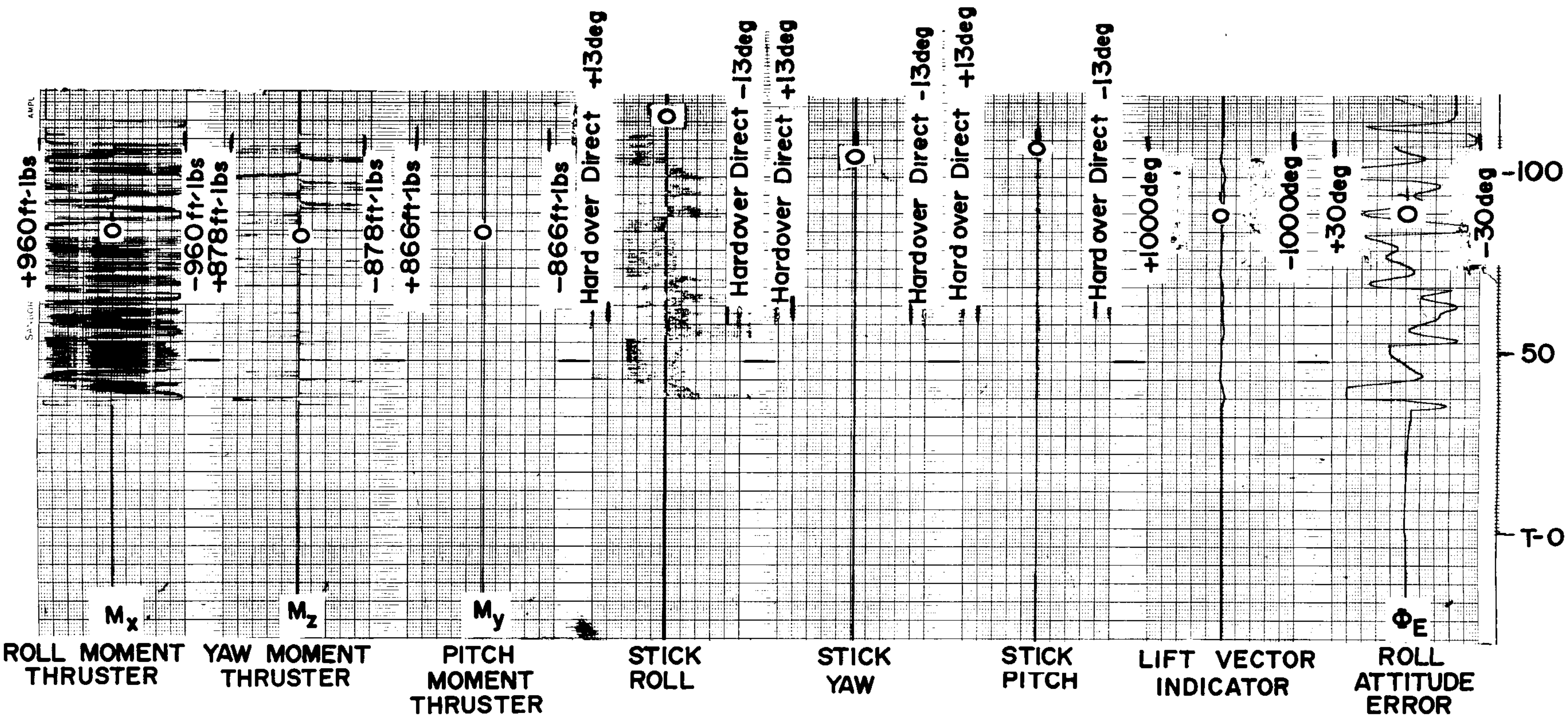


(a) RECORDER NO. 1

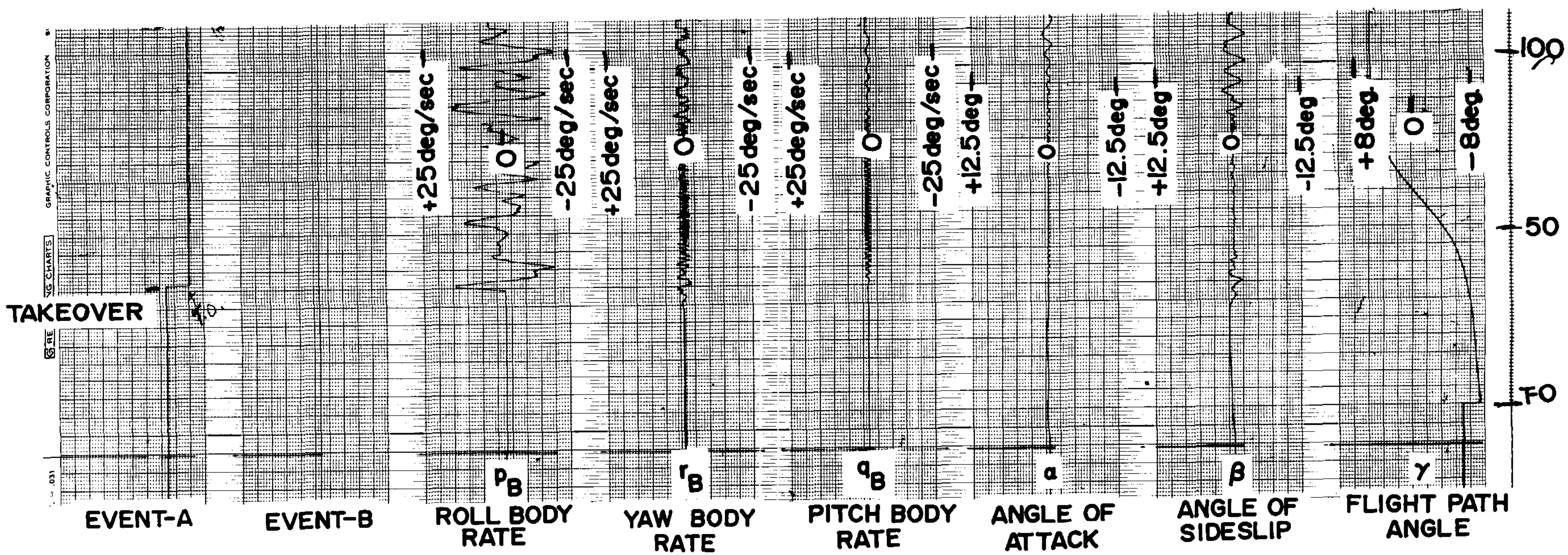
FIGURE 13 - CE 101 ~ SERVICE MODULE ABORT



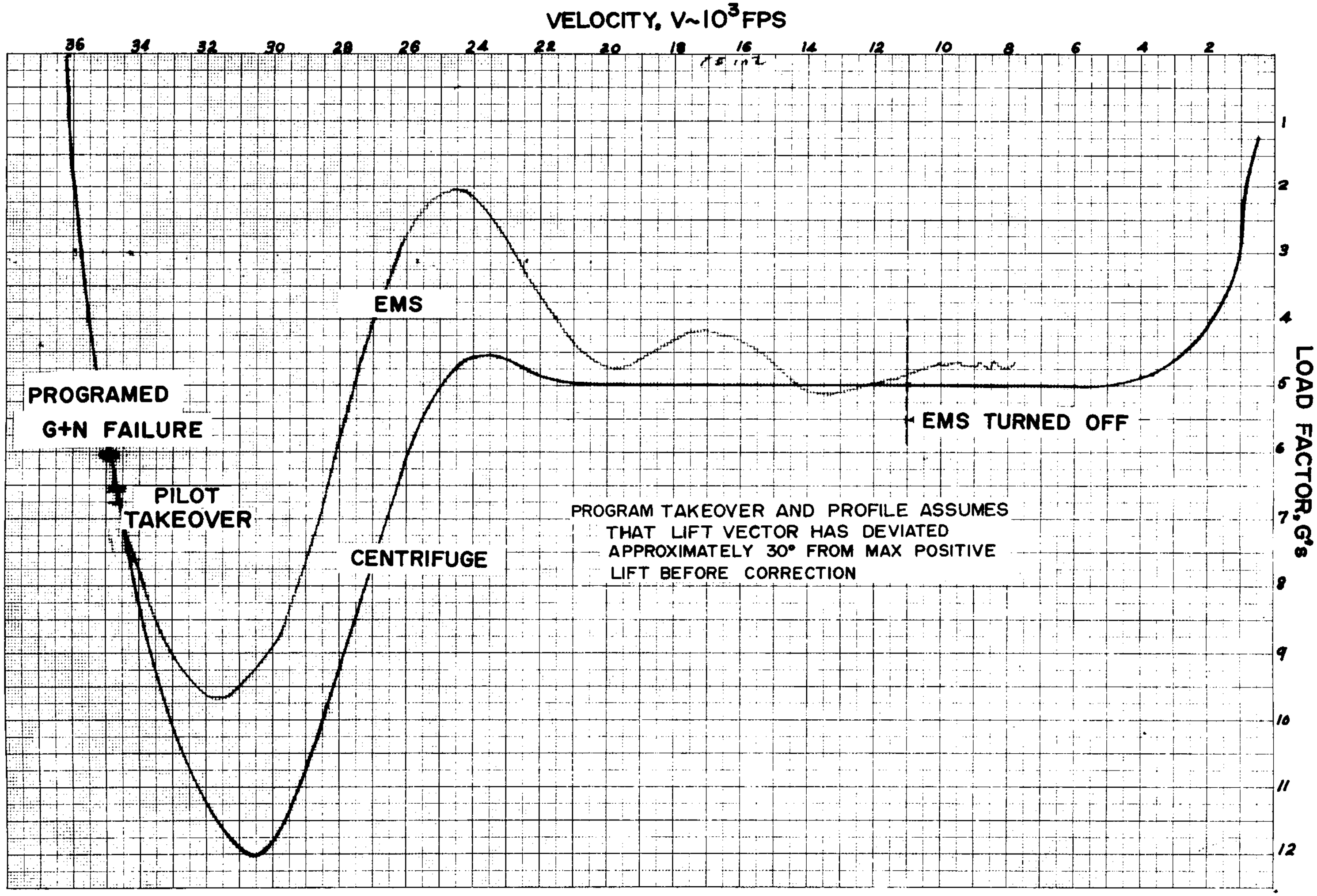
(b) RECORDER NO. 2
FIGURE 13 - CONTINUED



(c) RECORDER NO. 3
FIGURE 13 - CONTINUED

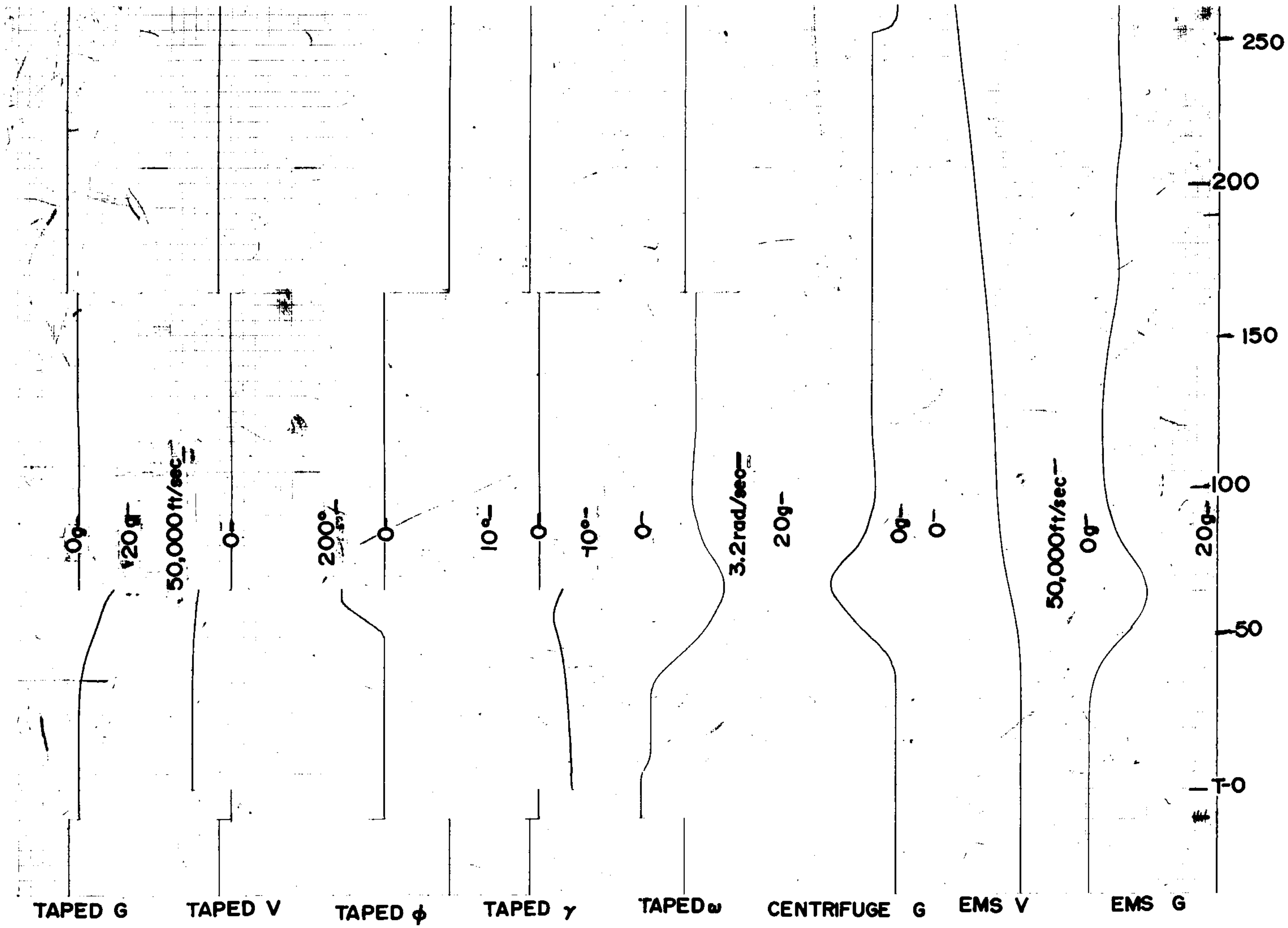


(d) RECORDER NO. 4
FIGURE 13 - CONCLUDED

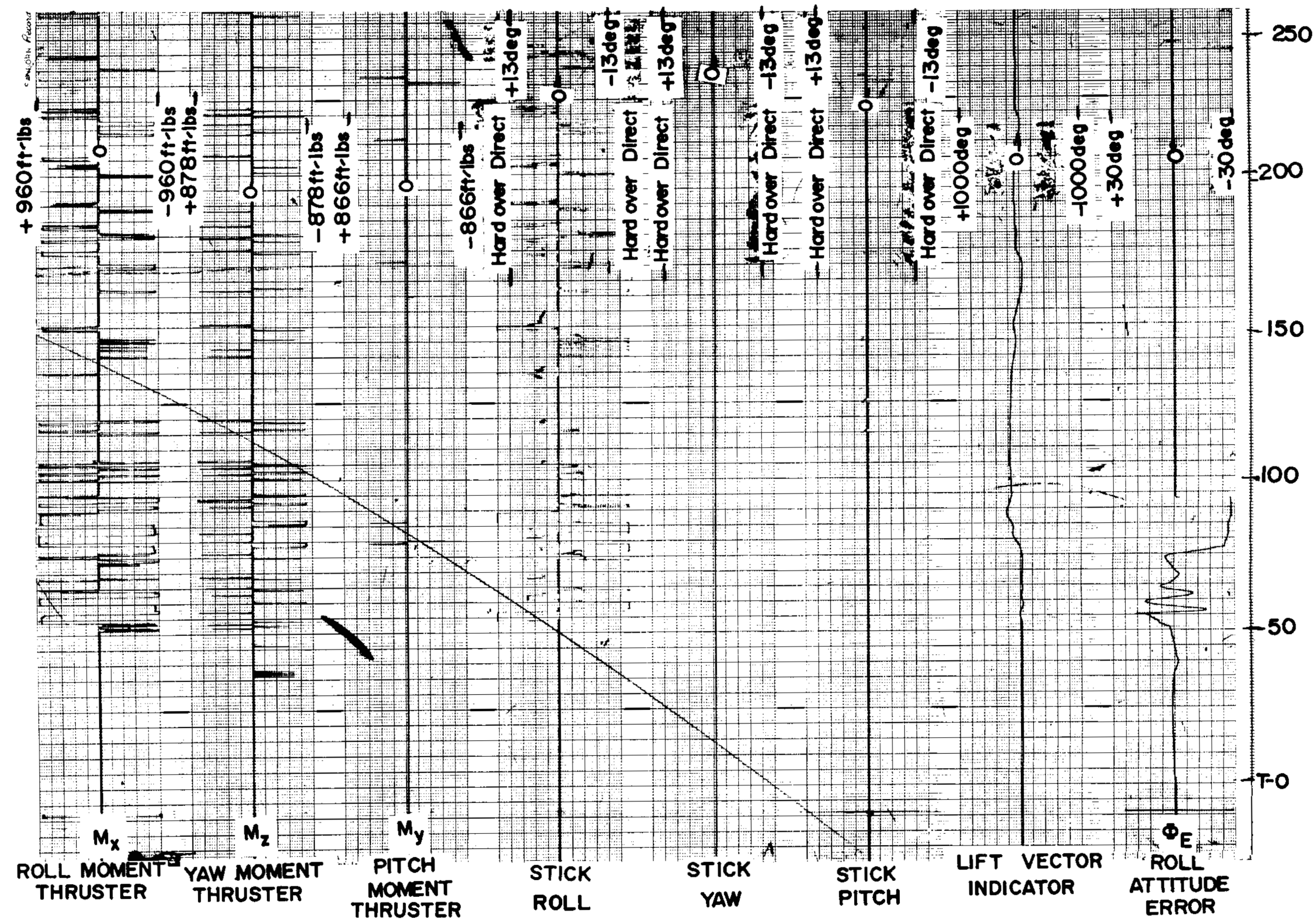


(a) RECORDER NO. 1

FIGURE 14 - CE 102 ~ BANK ANGLE COMMAND FAILURE (12g PEAK)



(b) RECORDER NO. 2
FIGURE 14 - CONTINUED



(c) RECORDER NO. 3

FIGURE 14 - CONTINUED

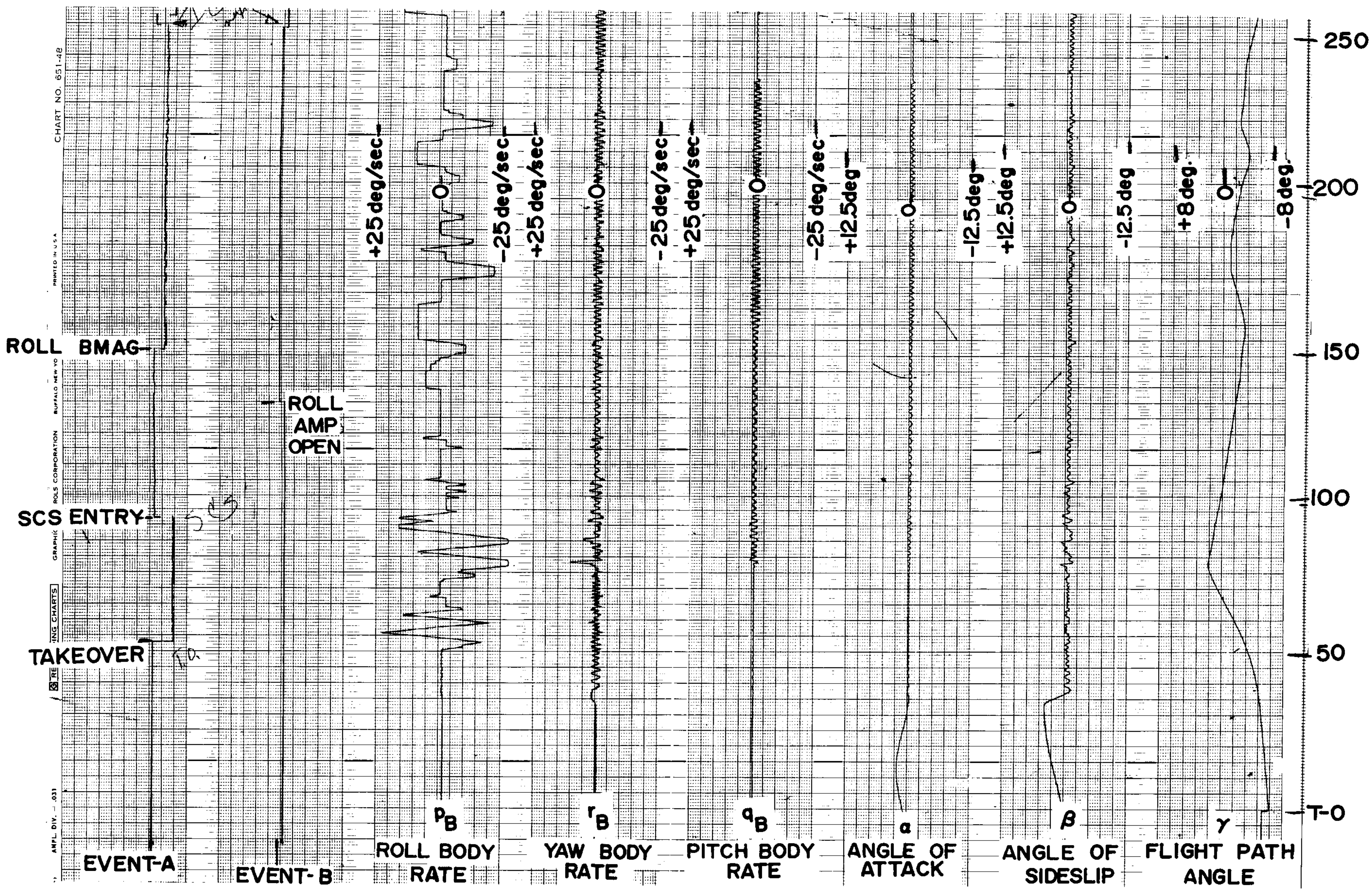


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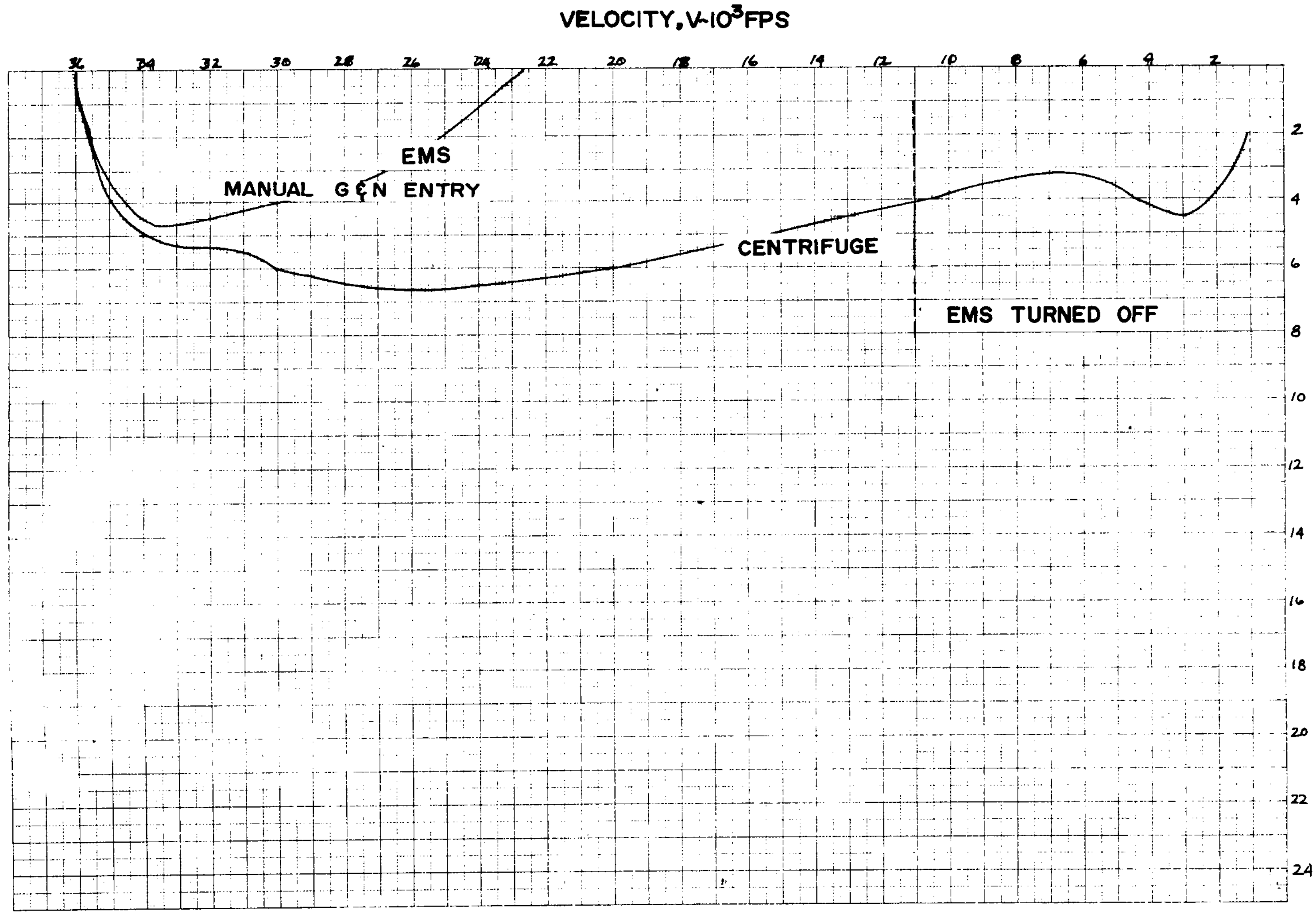
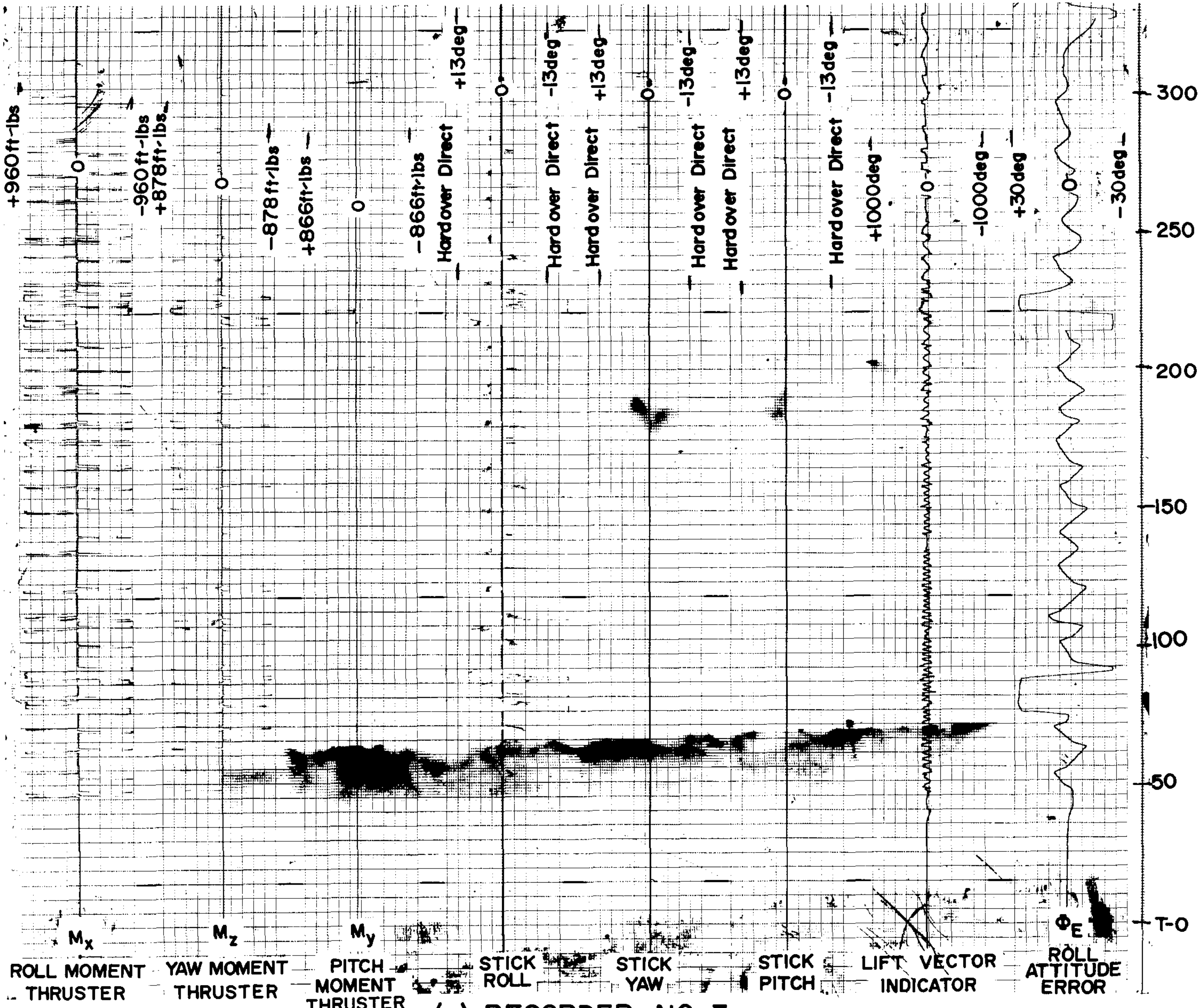
FIGURE 14 - CONCLUDED



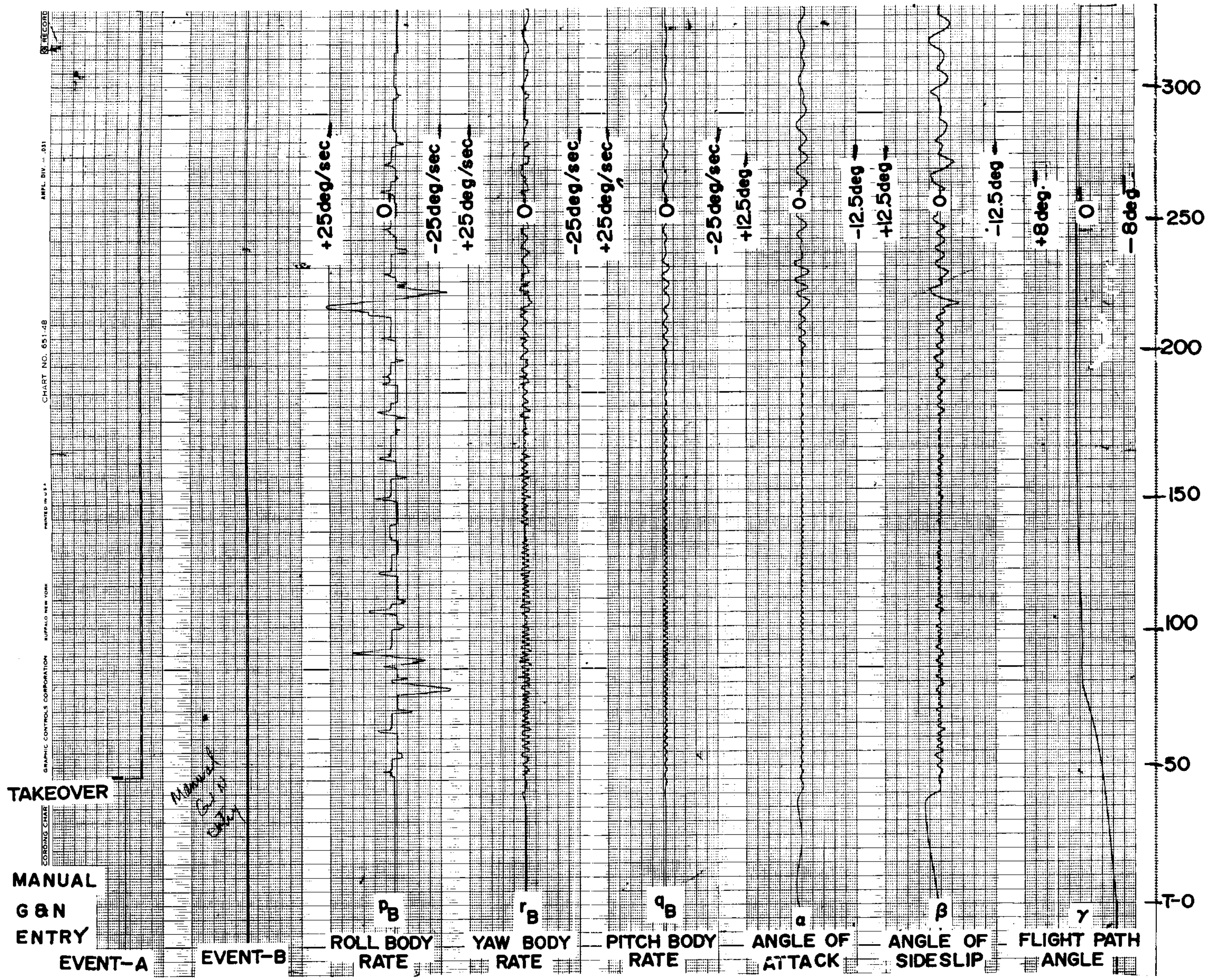
(a) RECORDER NO. 1

FIGURE 15 - CE 104 ~ NORMAL REENTRY (1000 N.M. RANGE)

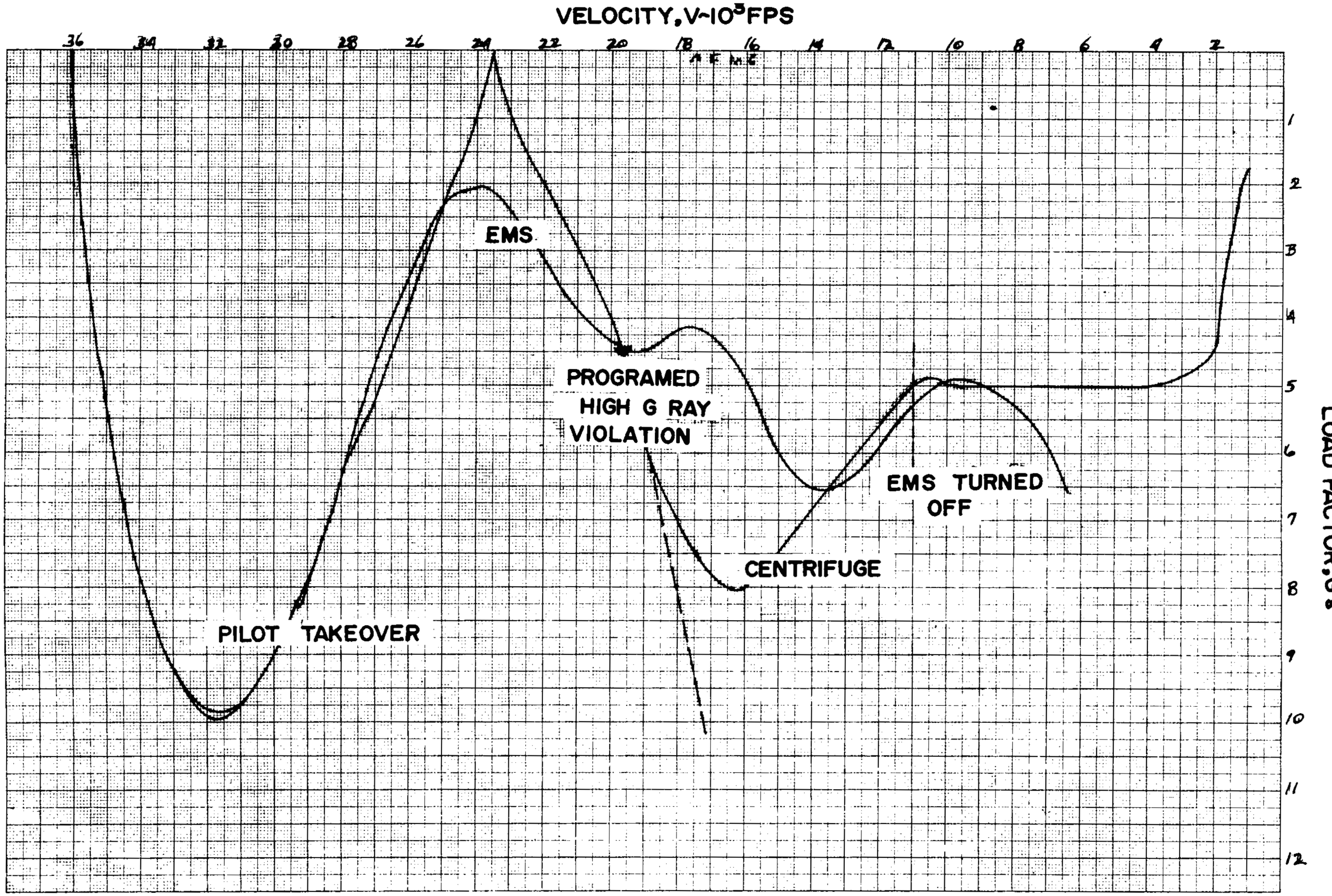
(b) RECORDER NO. 2
FIGURE 15 - CONTINUED



(c) RECORDER NO. 3
FIGURE 15 - CONTINUED

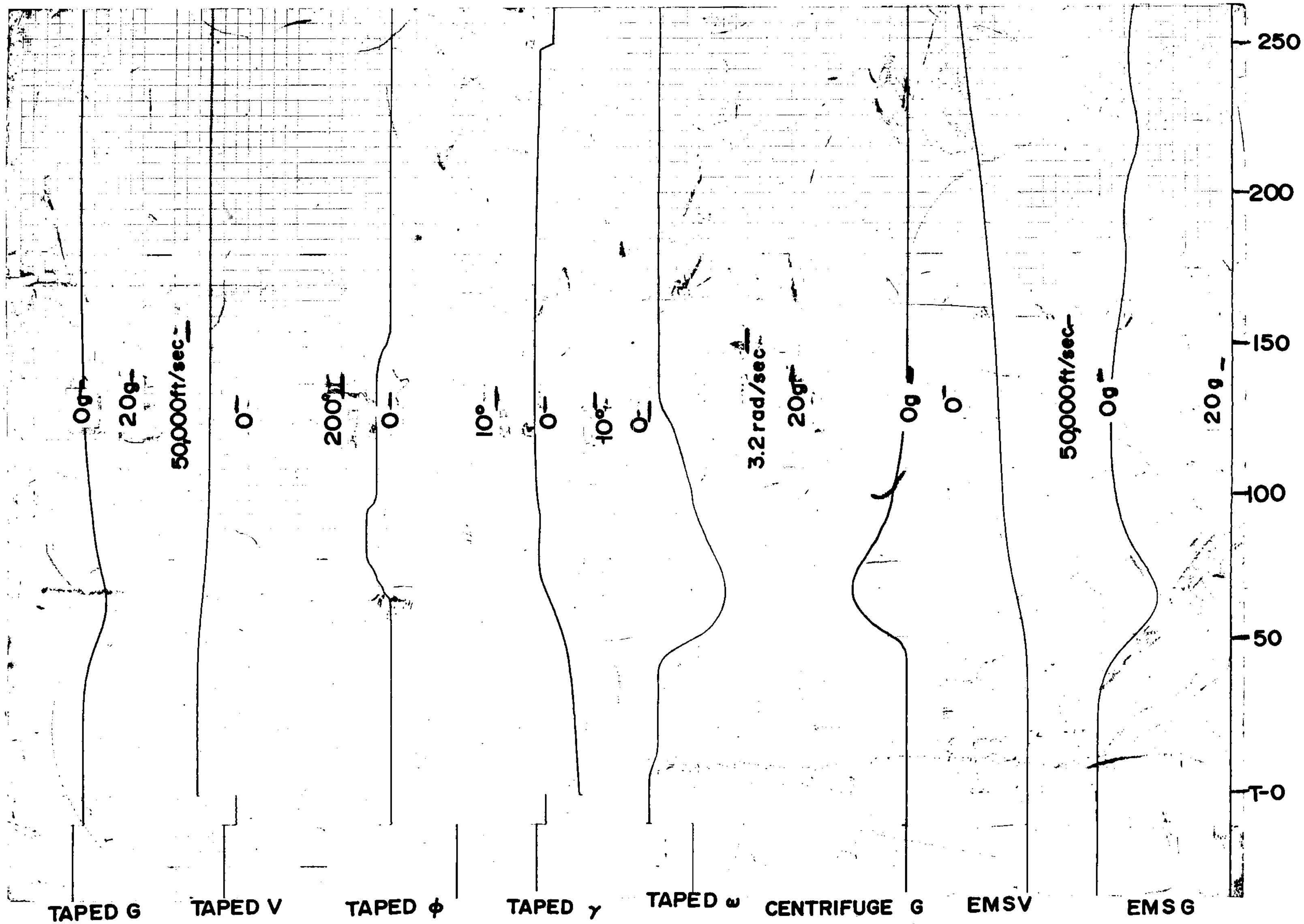


(d) RECORDER NO. 4
FIGURE 15-CONCLUDED

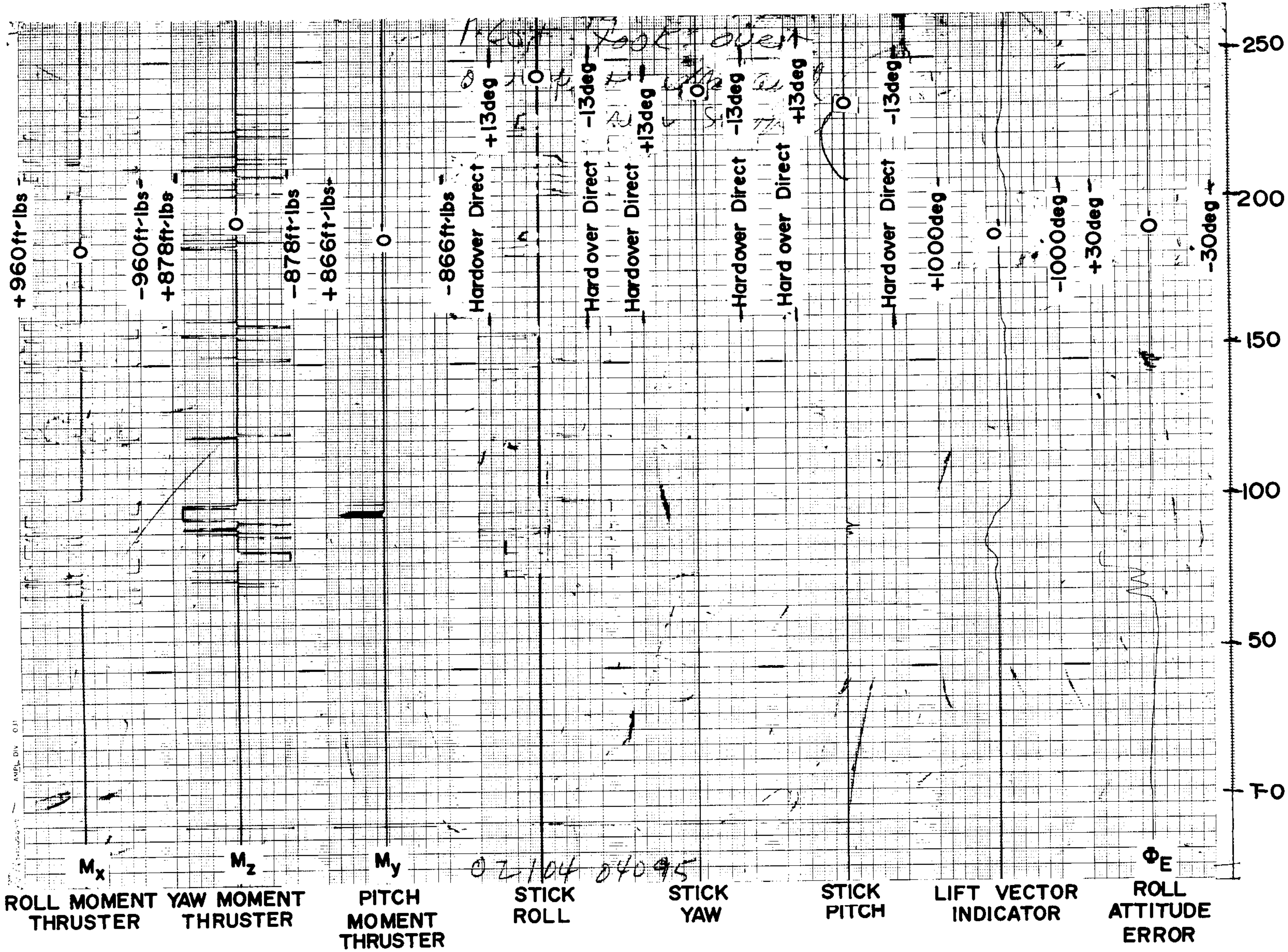


(a) RECORDER NO. 1

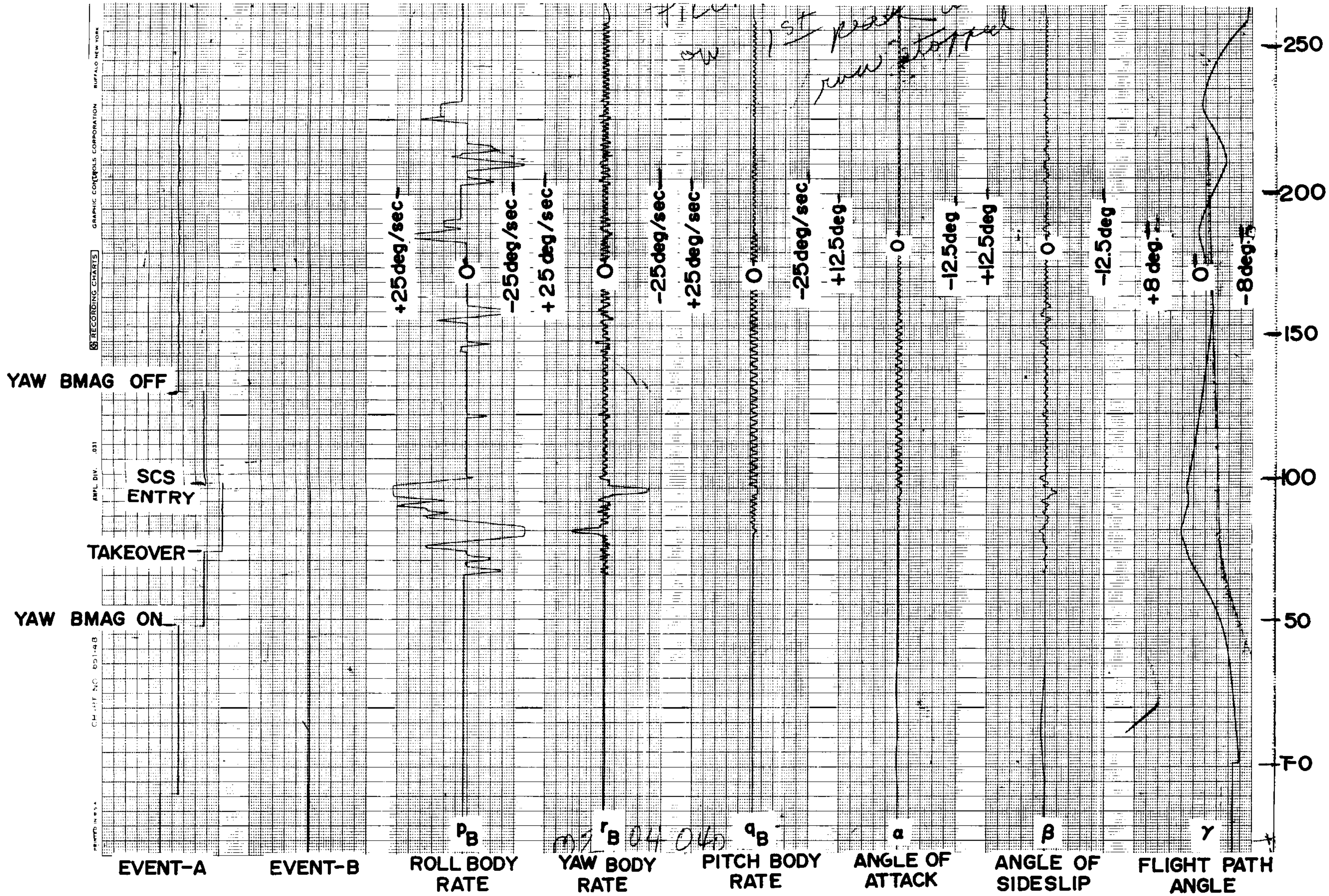
FIGURE 16 - CE 106 ~ HIGH-G RAY VIOLATION (10g PEAK)



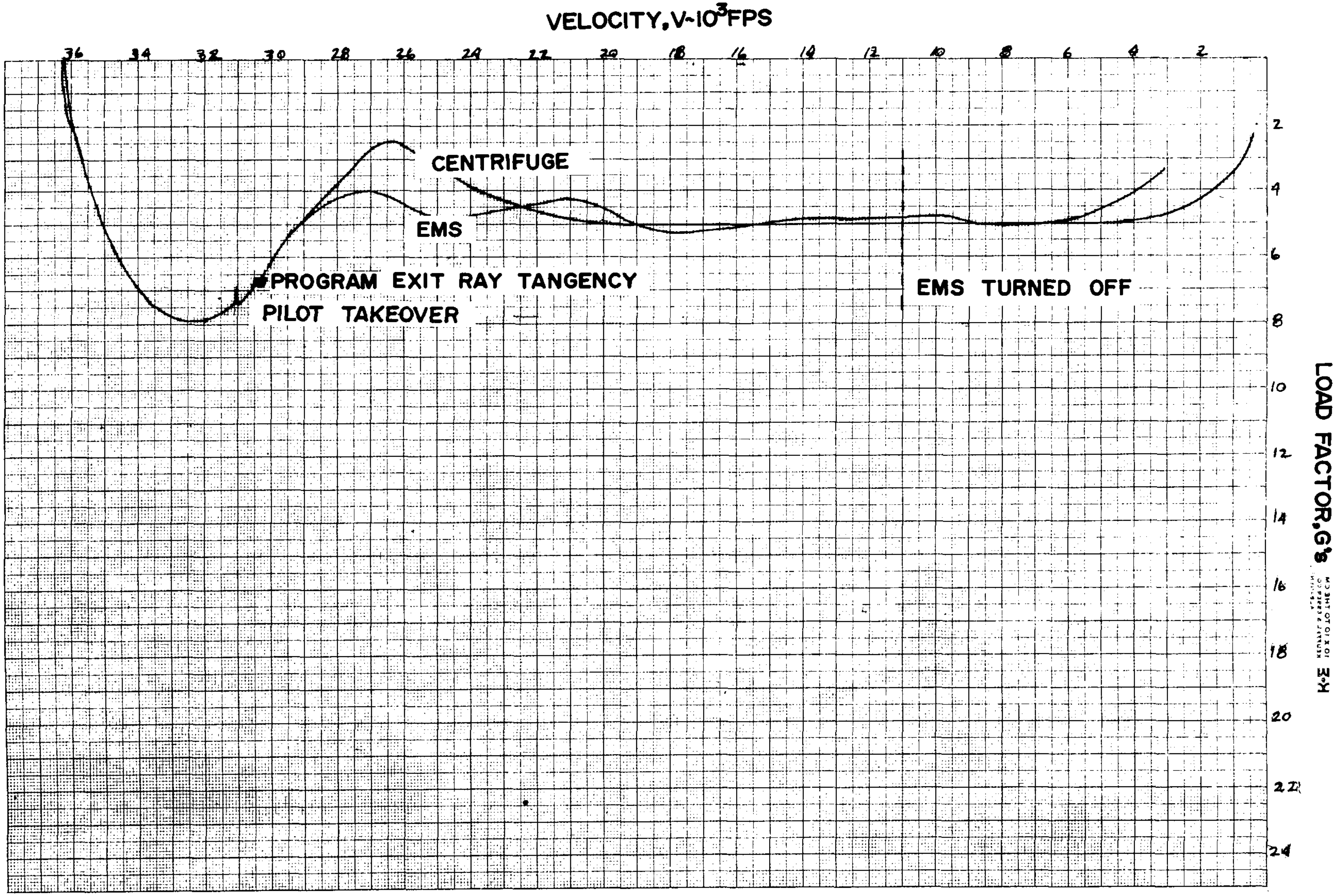
(b) RECORDER NO. 2
FIGURE 16 - CONTINUED



(c) RECORDER NO. 3
FIGURE 16 - CONTINUED

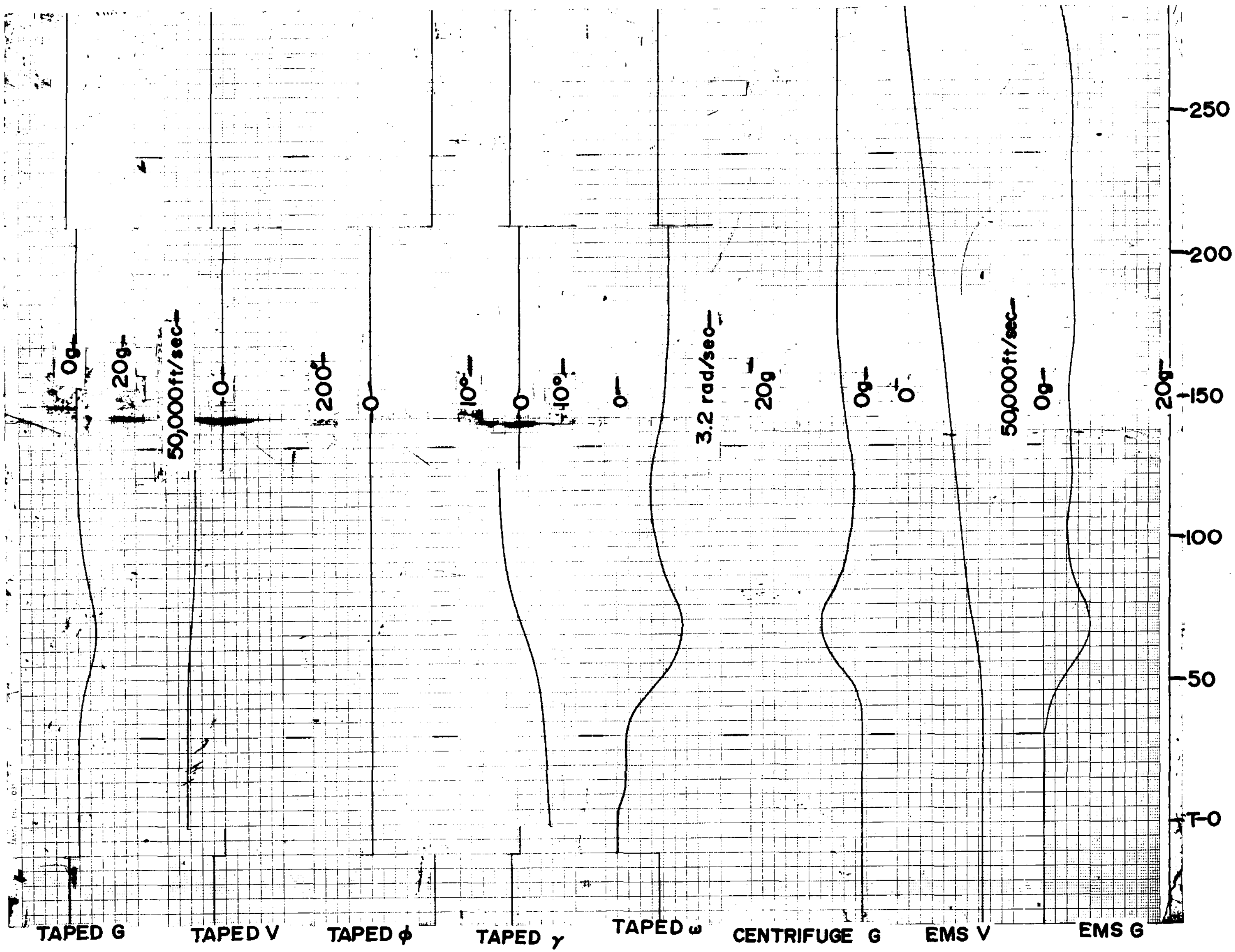


(d) RECORDER NO. 4
FIGURE 16 - CONCLUDED

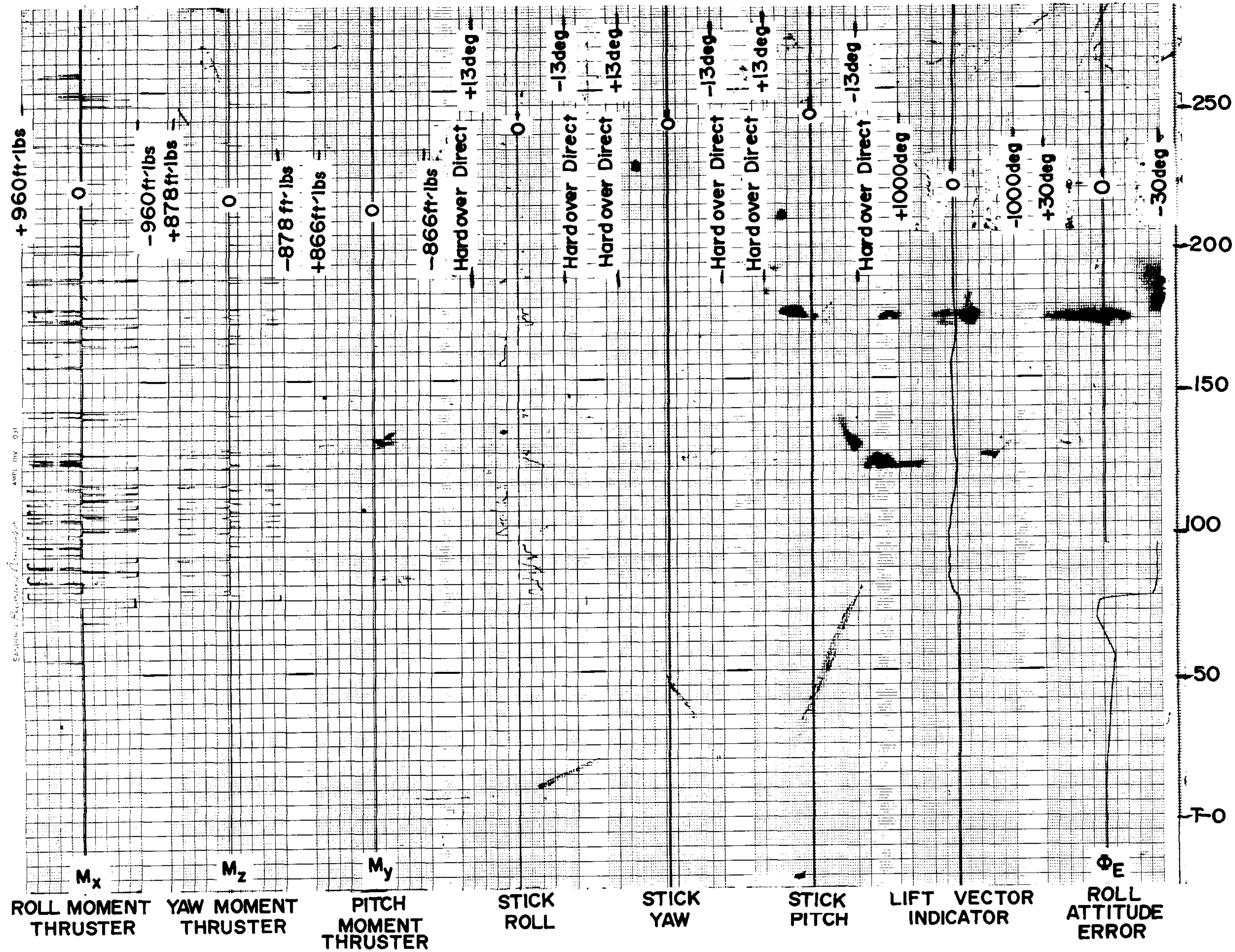


(a) RECORDER NO. 1

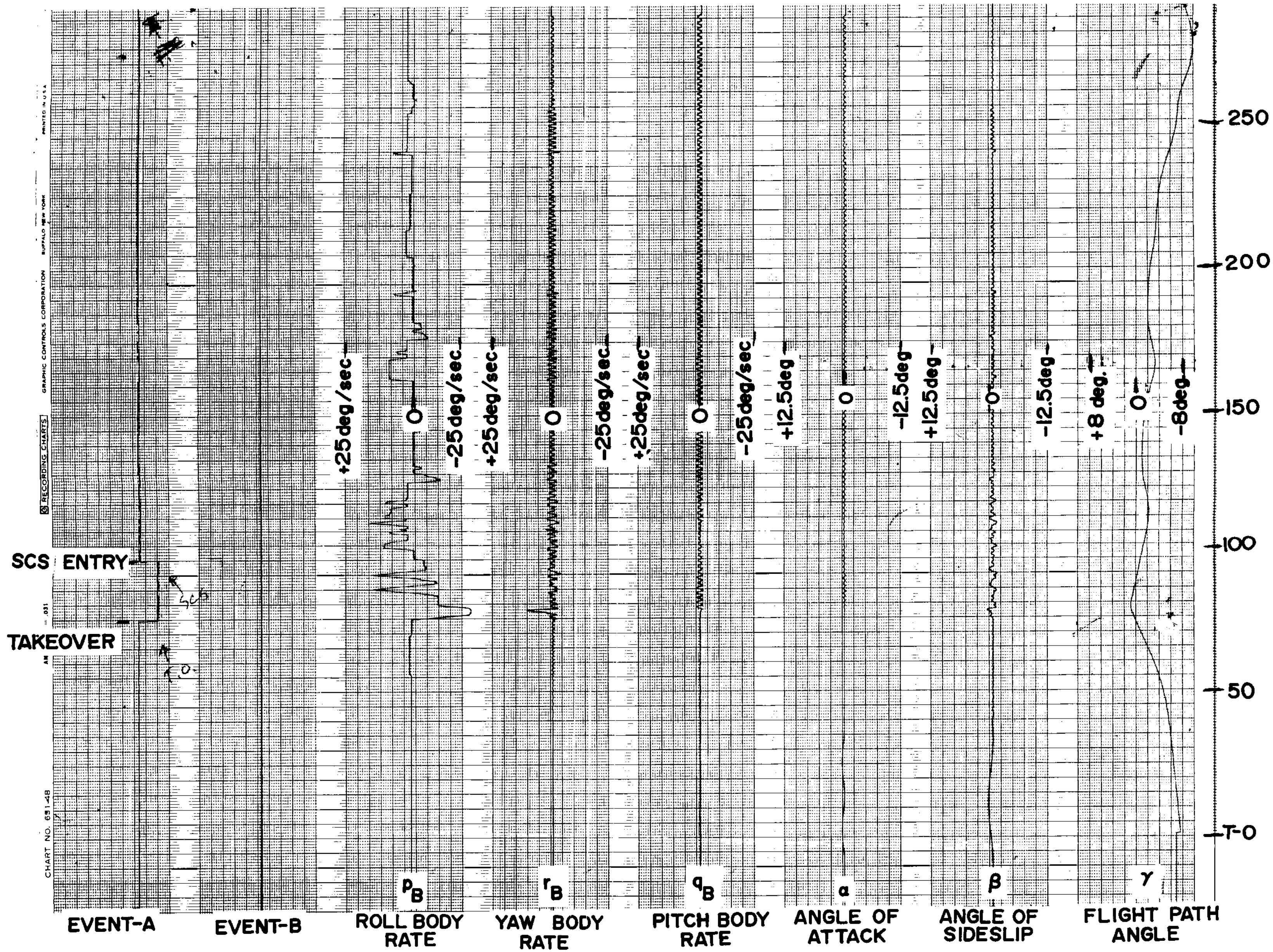
FIGURE 17 - CE 107 ~ EXIT RAY VIOLATION (8g PEAK)



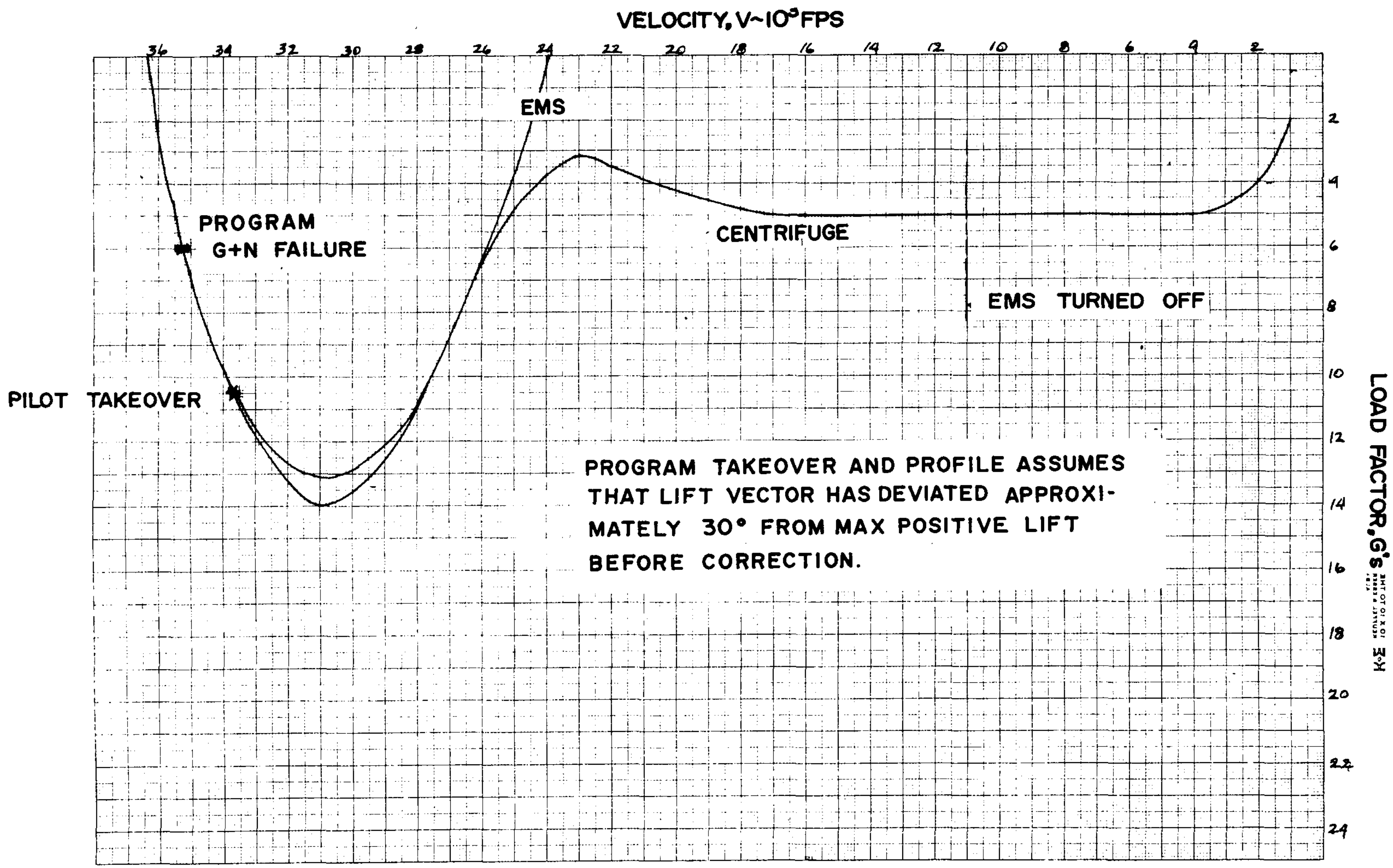
(b) RECORDER NO. 2
FIGURE 17 - CONTINUED



(c) RECORDER NO. 3
FIGURE 17-CONTINUED

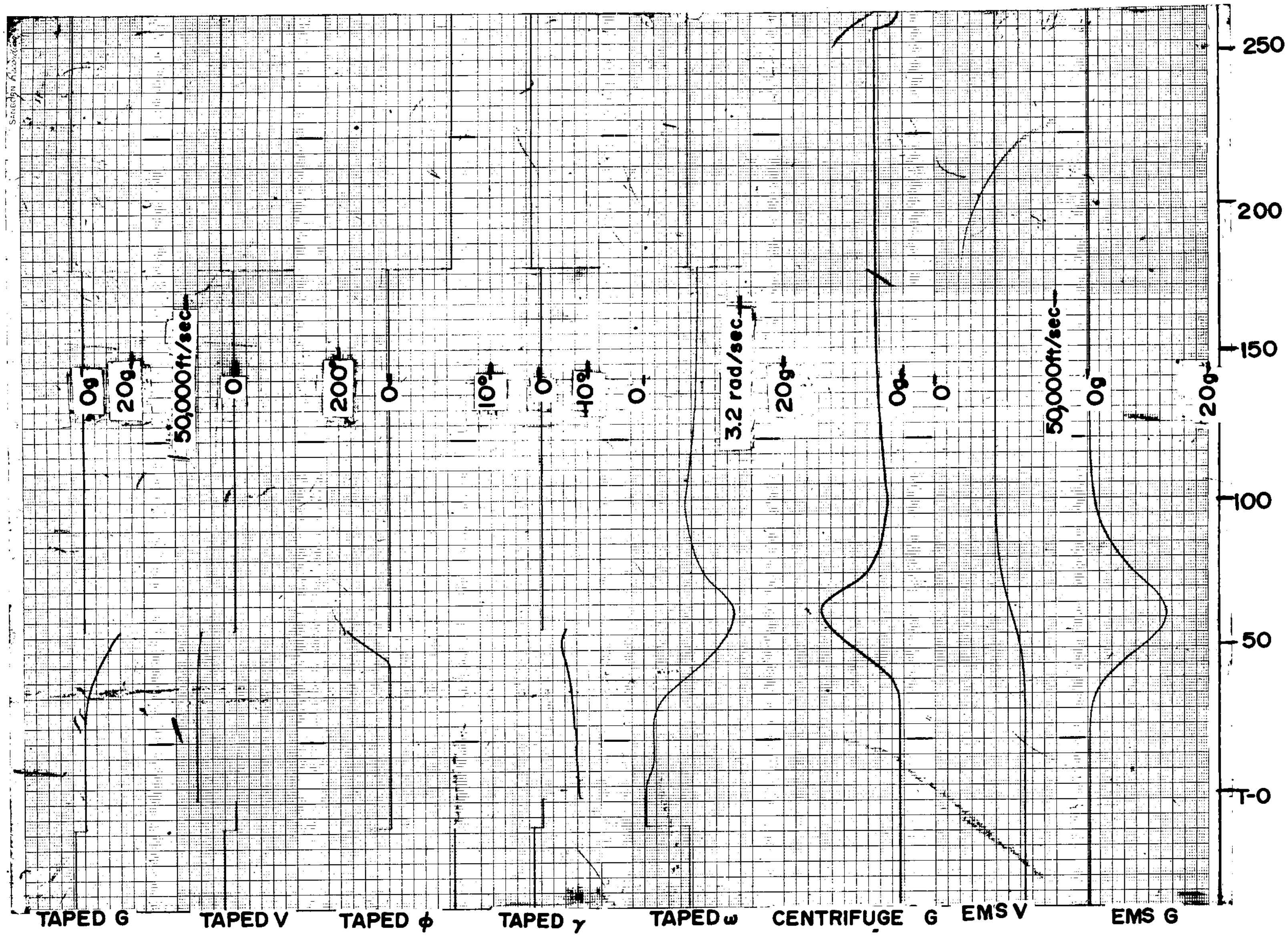


(d) RECORDER NO.4
FIGURE 17-CONCLUDED

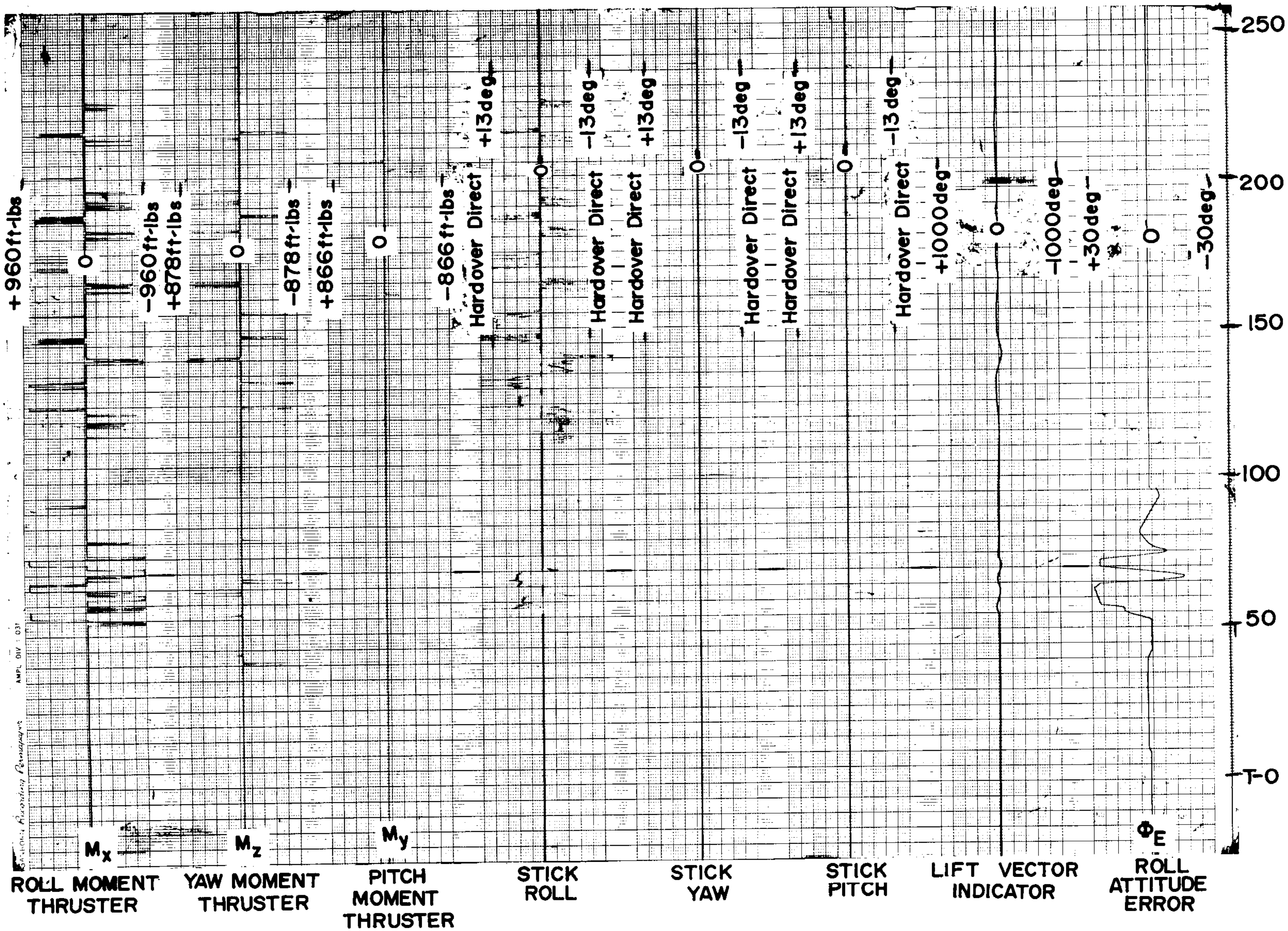


(a) RECORDER NO. 1

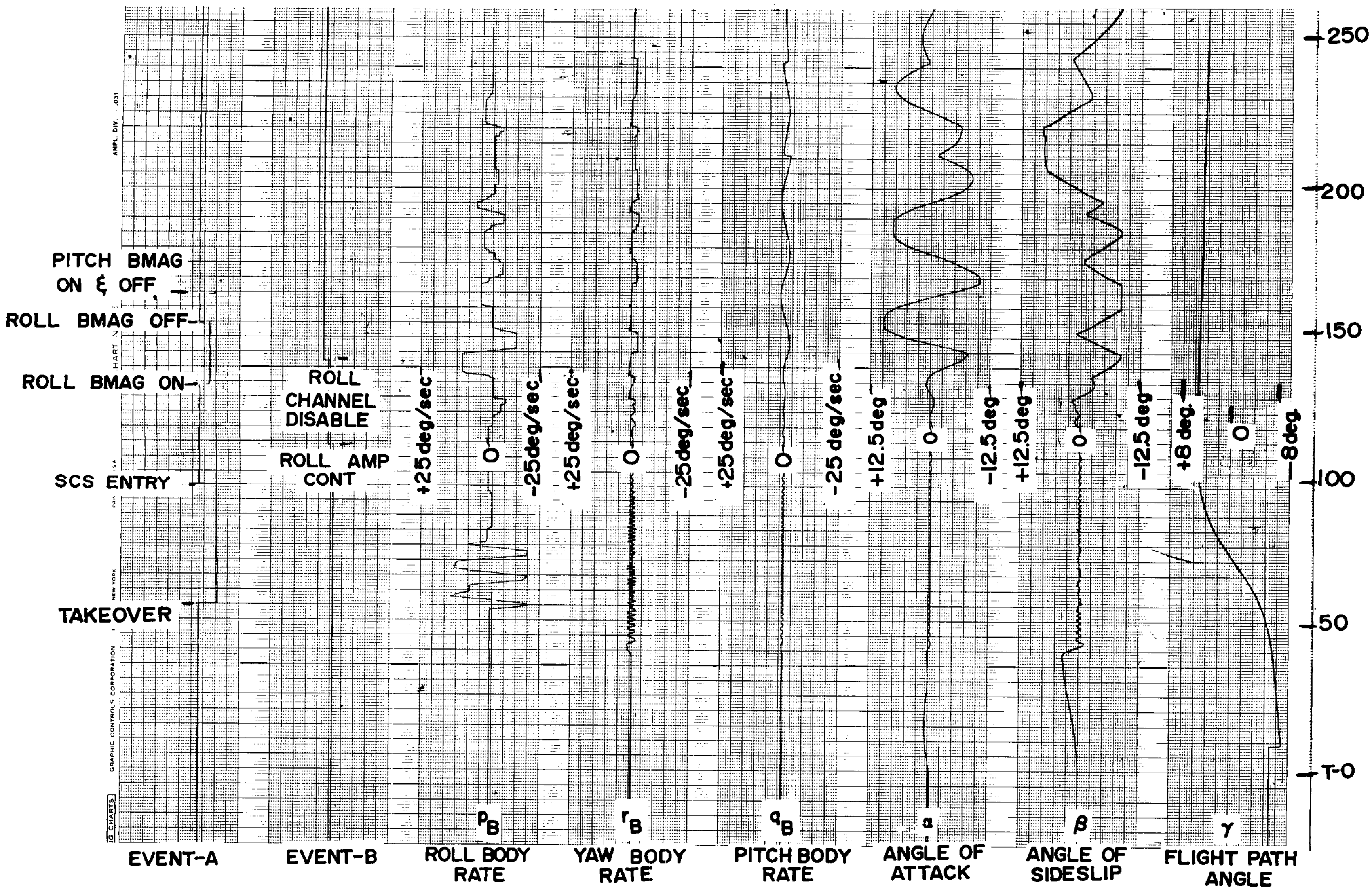
FIGURE 18 - CE 110 ~ BANK ANGLE COMMAND FAILURE (14g PEAK)



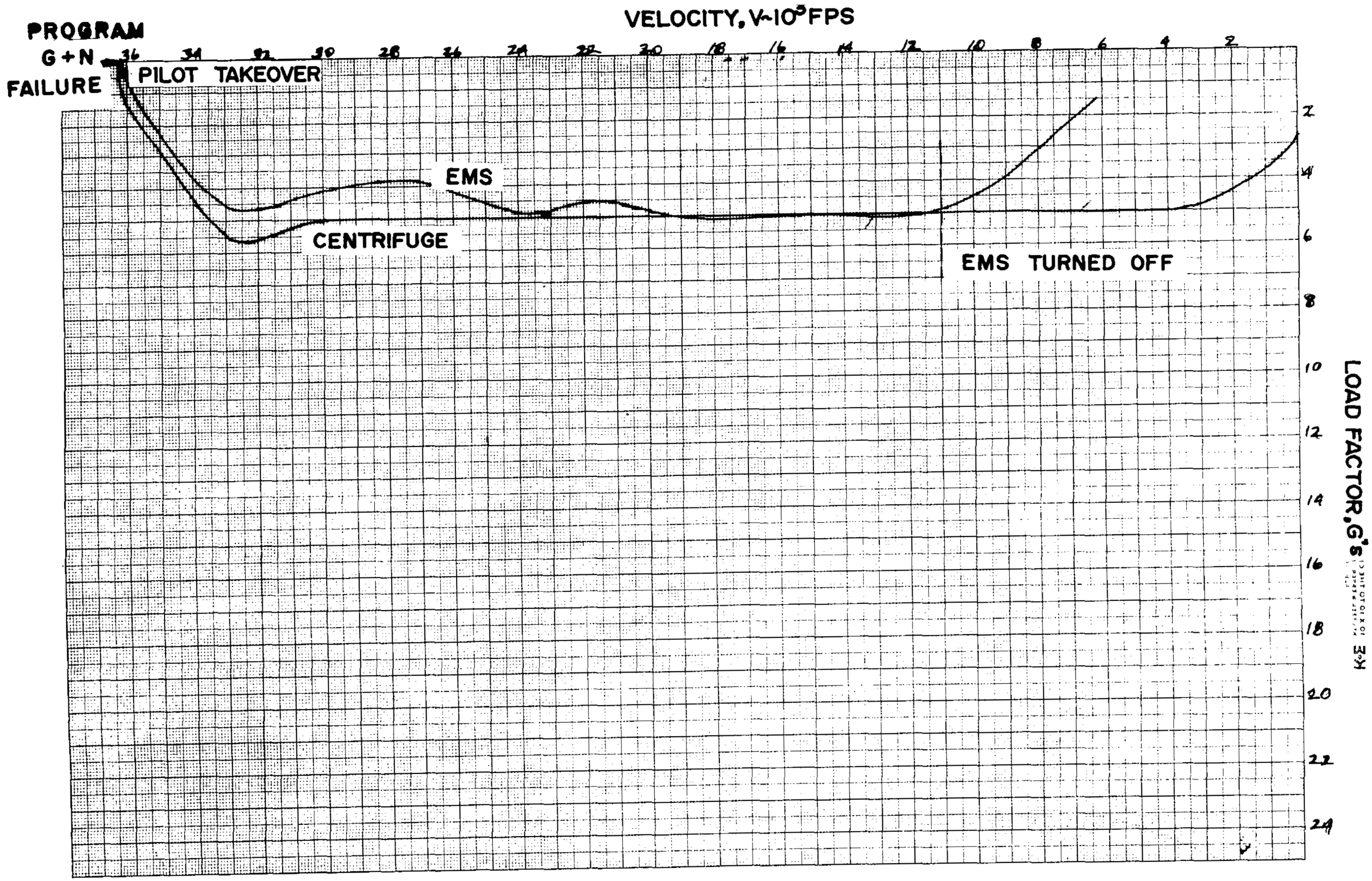
(b) RECORDER NO. 2
FIGURE 18 - CONTINUED



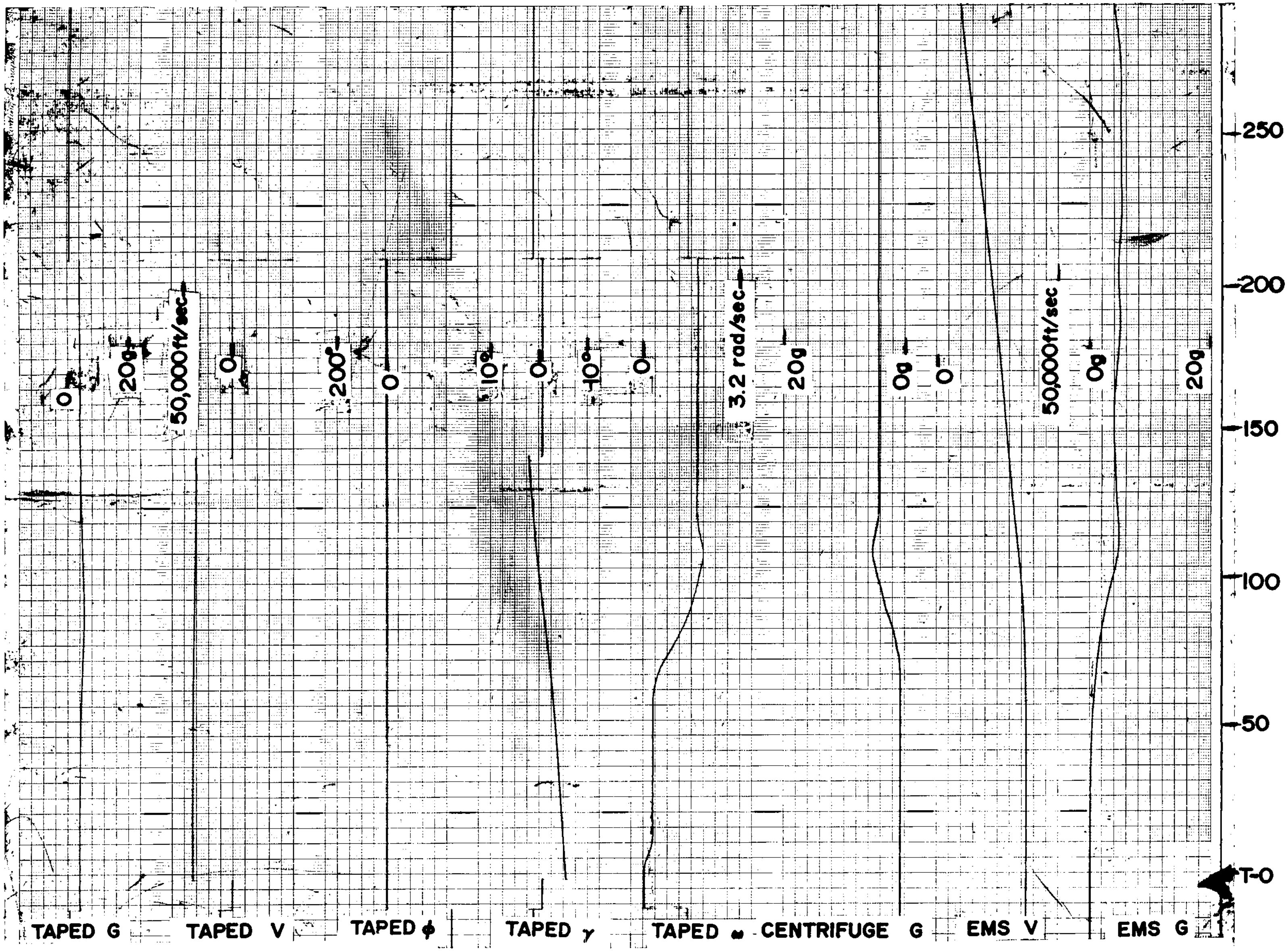
(c) RECORDER NO. 3
FIGURE 18 - CONTINUED



(d) RECORDER NO. 4
FIGURE 18 - CONCLUDED



(a) RECORDER NO. 1
FIGURE 19 - CE 114 ~ REENTRY GAMMA TOO SMALL (-5.30°)



(b) RECORDER NO. 2
FIGURE 19-CONTINUED

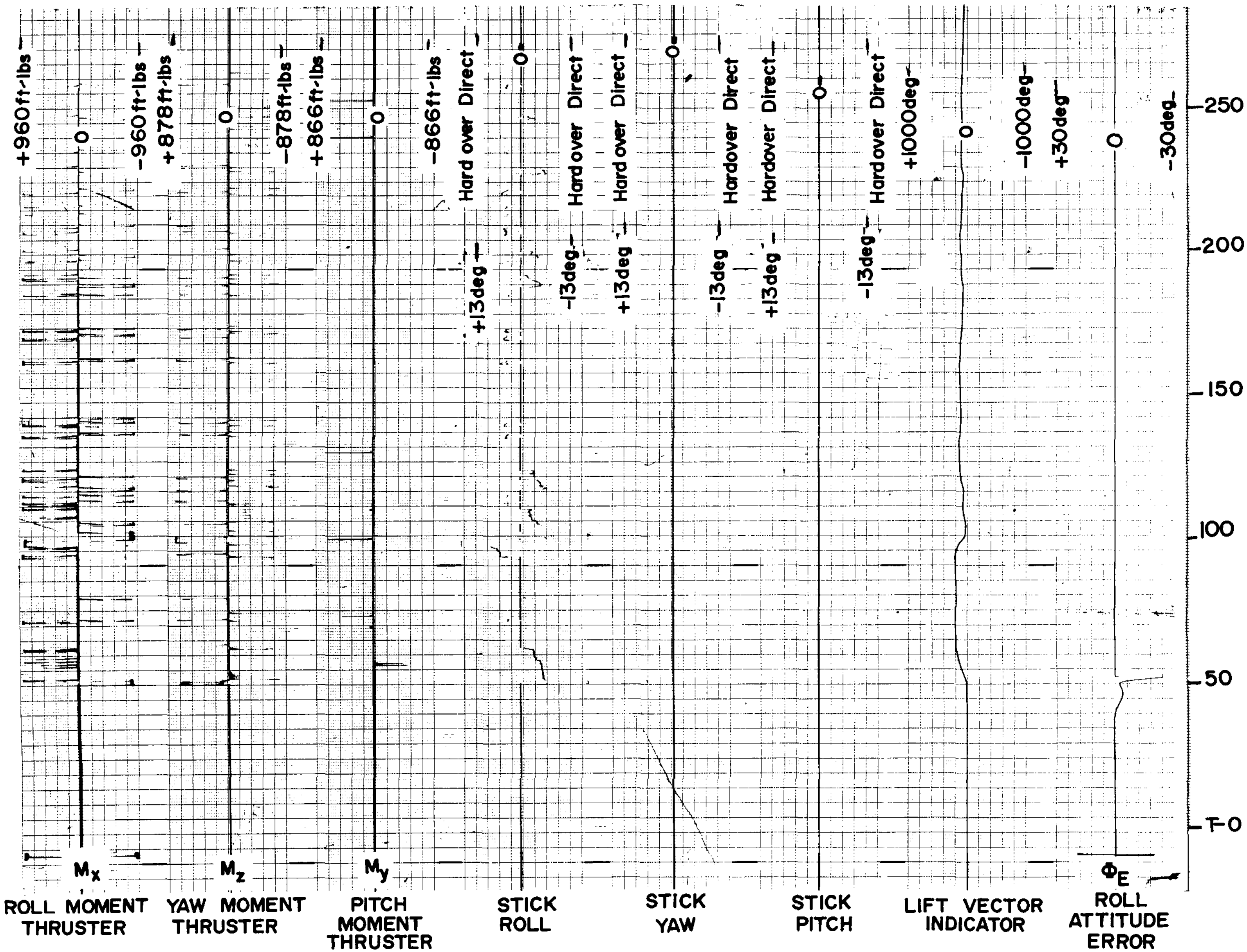


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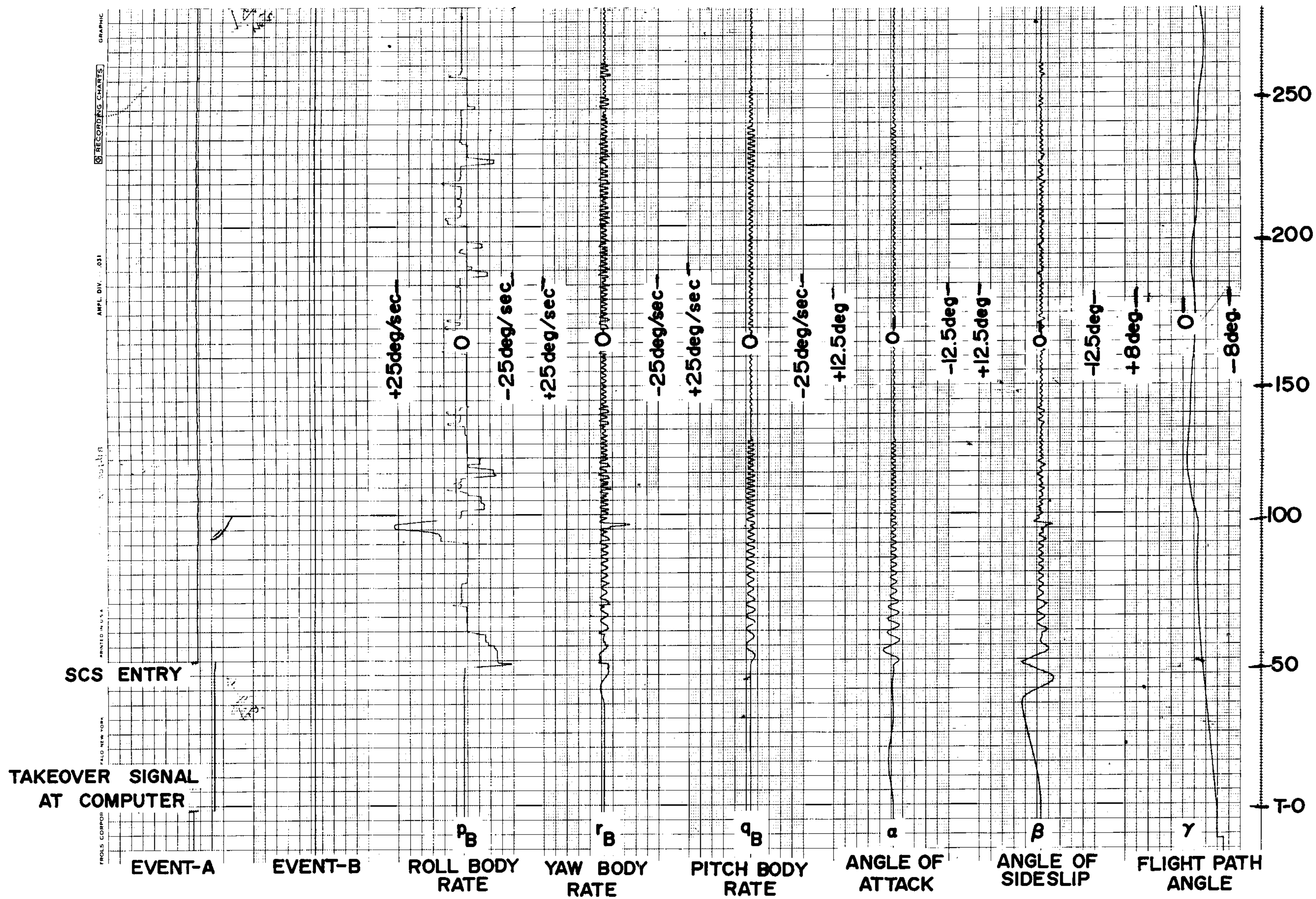
FIGURE 19 - CONTINUED



(d) RECORDER NO. 4
FIGURE 19-CONCLUDED

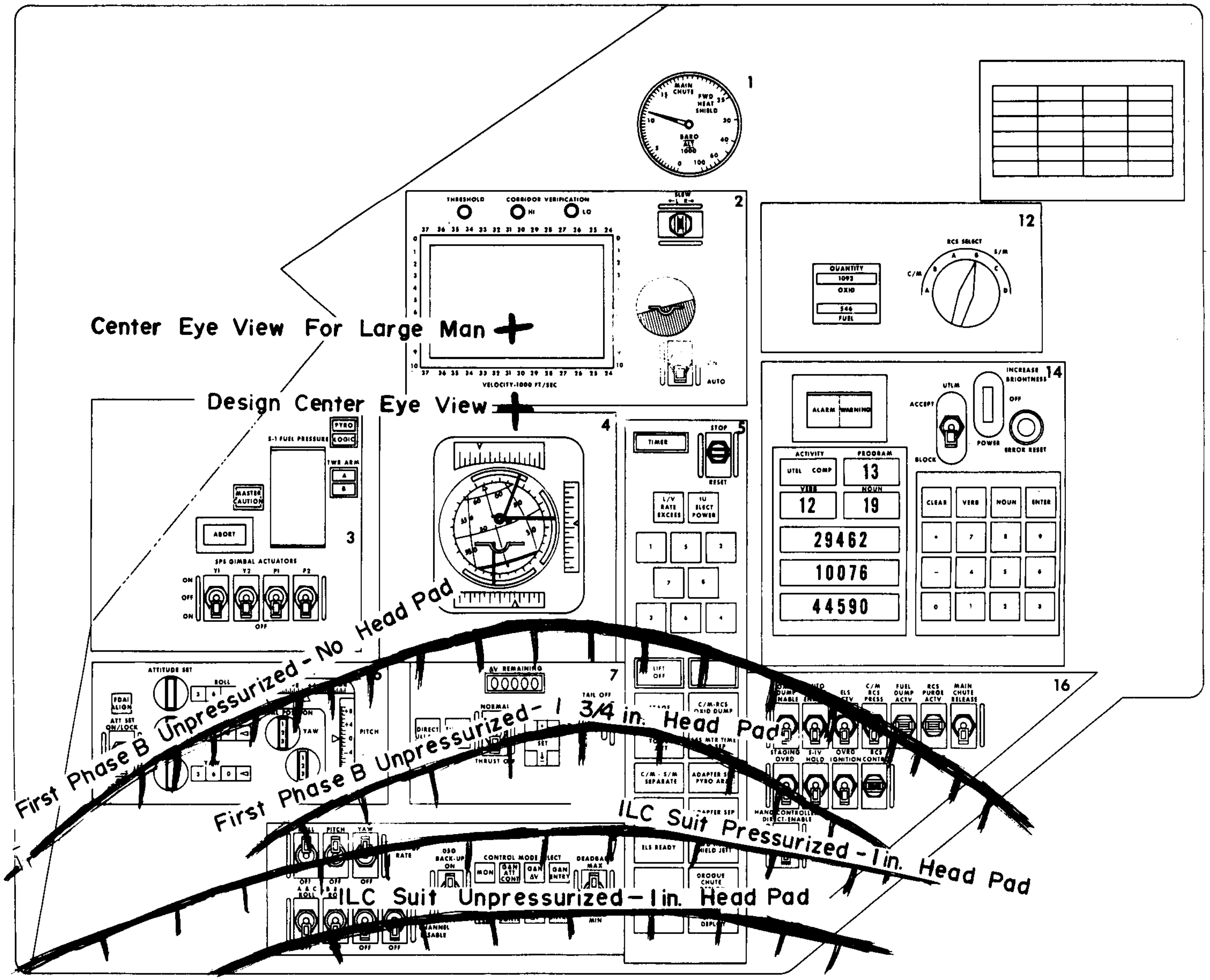


FIGURE 20: VISION LINES FOR FIRST APOLLO PHASE B AND ILC HELMETS

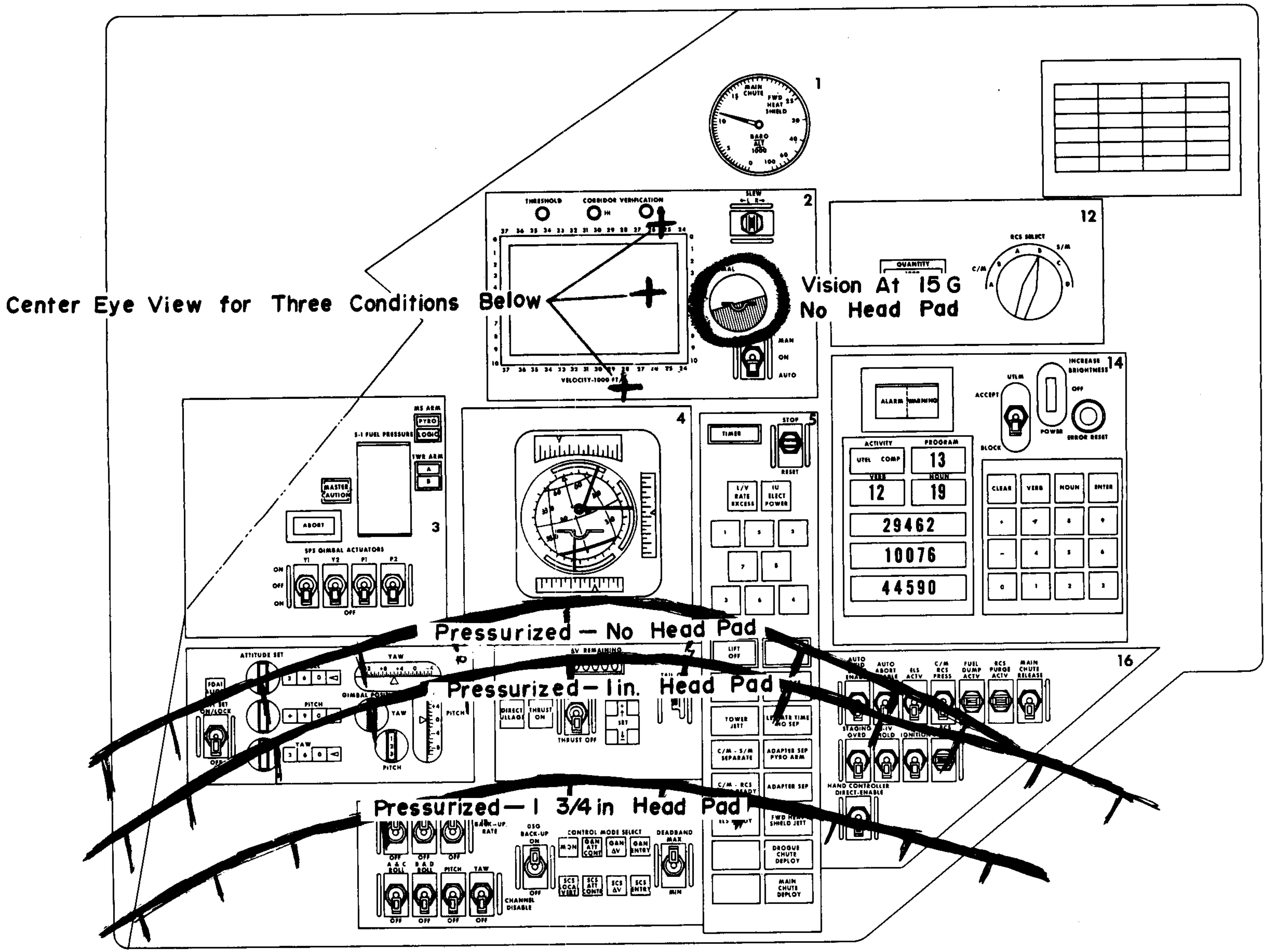


FIGURE 21: VISION LINES FOR SECOND APOLLO PHASE B HELMET